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AN ASSESSMENT OF STREET DUST AND OTHER SOURCES OF AIRBORNE PARTICULATE MATTER IN HAMILTON, ONTARIO

PREPARED
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ABSTRACT

Traditional industrial sources of particulate matter have been subjected to increasingly stringent regulations during recent years and significant reductions in total suspended particulate matter (TSP) concentrations have been achieved in most industrialized cities. However, trends in ambient TSP levels indicate that, despite continuing abatement efforts by industry, air quality objectives may not be realized through control of traditional industrial sources alone. Hence there is a need to assess the relative impact of other sources, such as particle reentrainment caused by wind and traffic, on the observed TSP loadings in urban areas. A comprehensive study designed to characterize atmospheric particulate matter, define the importance of various source categories, and evaluate street cleaning methods was initiated in 1979 in Hamilton, Ontario.

Detailed studies of TSP loadings at several sites in Hamilton were conducted over a 3-month period. In addition to assessing the general features of the data, the collected samples were analyzed for a broad range of chemical constituents. These results, as well as dispersion and receptor models, have been used to characterize particulate matter and to assess in detail the relative contribution of various source types to TSP loadings in the Hamilton area.

At the study site located in downtown Hamilton, traffic-related sources were the largest contributor (∿ 40%) to TSP levels during the study period, followed by background (∿ 35%), and area sources (∿ 10%) such as unpaved parking lots and streets. Point sources were found to contribute only ∿ 7% to TSP loadings in the study area, despite their obvious presence and significant impact under certain meteorological conditions. It should be noted that periods of adverse dispersion conditions which can result in the accumulation of industrial and other emissions in the Hamilton area appear to have occurred somewhat less frequently than usual during the study period.

The evaluation of street cleaning methods showed that more frequent mechanical sweeping had no measurable effect on TSP levels. A small decrease (∿ 7%) appears to have occurred as a result of more frequent vacuum sweeping, but statistical tests suggest that the observed change is only of marginal significance. The receptor model results indicate that mechanical or vacuum sweeping produced a statistically significant but small increase or decrease, respectively,

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in the relative contribution of the coarse road dust component, amounting to only one to three $\mu g/m^3$ in either direction. Thus, under most circumstances, more frequent sweeping of roads and streets is unlikely to achieve appreciable reductions in urban TSP levels.

The results of the Hamilton study have been used to define those experimental approaches suitable for use in future assessments of urban particulate matter.

EXECUTIVE SUMMARY

INTRODUCTION

Although a substantial reduction in suspended particulate matter concentrations in urban atmospheres has been realized over the last decade, mainly through control of industrial point sources, analysis of trends in total suspended particulate matter (TSP) levels during this period indicates that TSP air quality objectives may not be realized through control of these traditional sources alone. The preponderance of evidence from the results of several studies that have been conducted to investigate the urban TSP problem leaves little doubt that resuspension of particles can make a substantial contribution to urban TSP levels and thus is a significant limitation to the attainment of TSP air quality objectives in urban areas.

OBJECTIVES

This study of urban road dust as a source of suspended particulate matter was undertaken to provide information which can be used to develop comprehensive and effective urban particulate matter control strategies in Canada. The study was carried out in Hamilton, Ontario and its specific objectives were:

i) to develop a better understanding of the predominant factors determining particulate matter concentrations in Hamilton. The specific goals defined to meet this objective were:

- to characterize the physical and chemical composition of individual size fractions of urban particulate matter
- to identify predominant source categories of urban particulate matter and quantify their contribution to ambient levels in downtown Hamilton
- to determine the effect of major independent variables such as meteorology, traffic patterns, and urban characteristics on the extent of particulate matter reentrainment
- to evaluate street sweeping methodologies.

ii) to use the above results to define a suitable methodology for the development and evaluation of particulate matter control strategies for urban areas.

METHODOLOGY

Seven monitoring sites were established, four of these located on Cannon St., a major artery in downtown Hamilton. Two of these sites were chosen as the major focus for the experimental studies. At the Experimental site, street cleaning methods were assessed and other studies to define more precisely the contribution of road dust to measured TSP levels were conducted. The Control site on Cannon St. was used for control studies during the assessment of street sweeping methods. Two other sites on Cannon St., the John St. and Oak Ave. sites, were used to assess variations in TSP levels along the street. Three monitoring sites were established as background sites; one at the Stelco Research Centre to the north of the city, one at a school in the Beach Boulevard area to the northeast, and one at a farm on Hamilton Mountain to the south.

TSP levels were monitored at all sites using high-volume samplers. At the Experimental and Control sites, the variation of TSP levels with height was monitored, and, at the Experimental site, the variation of TSP levels with distanc away from the road also was monitored. In addition, the following parameters were monitored at the Experimental and Control sites:

- carbon monoxide
- coefficient of haze
- traffic counts
- particle sizing using dichotomous samplers
- dustfall.

In addition, the following experiments were conducted at the Experimental site:

- application of europium chloride tracer to assess the surface road dust contribution to TSP
- determination of the effects of street sweeping. This was accomplished by dividing the study period into three periods which were consecutively a baseline period, a period of daily mechanical sweeping of a half mile radius area around the

site, and a period of daily vacuum sweeping of the same area.

Samples of surface road dust material were collected from Cannon St. at the four sampling locations to assess loadings and to characterize this source.

A variety of methods were used to analyze and assess the samples. This variety was used so as to assess the usefulness of each method for application in subsequent studies. The analysis methods used were:

- X-ray fluorescence spectroscopy on the dichotomous filter samples for thirty elements
- Ion chromatography on glassfibre and cellulose filters predominantly to determine levels of sulphate, nitrate, chloride and ammonia
- Atomic absorption spectroscopy on extracts of glassfibre and cellulose filters to determine levels of manganese, copper, iron, lead, zinc and nickel
- Nuetron activation analysis of samples collected on cellulose filters for 24 hours after each $EuCl_3$ tracer application in order to determine levels of Eu and other elements (As, Co, Cr, Cu, Fe, Mn, Ni, Sb, Se and Zn) and thus assess the direct effect of road dust on TSP levels
- Optical microscopy on glassfibre filters to assess the cumulative effect of winds across the Hamilton airshed on the particulate species collected.

The data generated by the TSP determinations and chemical and physical analyses were reduced, stored and assessed using computer techniques. Source apportionment studies made use of three techniques:

- Microinventory - this involves an orderly compilation and quantitation of particulate sources in the vicinity of an air sampling site. Statistical regressional analysis is then used to quantify the relationship between particulate emissions, monitor siting characteristics, and experimentally measured ambient TSP levels. The regressional analysis uses annual geometric mean TSP concentration values as the dependent variable and three independent variable terms which account for the influence of area, point and local sources on ambient TSP levels.

- Dispersion Modelling - this technique begins with the source emission rate of a particular pollutant, applies a physical model of the atmosphere based on fluid mechanics to calculate the resultant concentration of the pollutant at any point away from the source. The model used in this study, PAL, allows for assessing the effects of point, area and line sources on ambient TSP air quality.
- Chemical Mass Balance (CMB) - this technique is a form of receptor model in which the detailed relative chemical composition of the particles emitted by each contributing source (source profile) and the same data available for one or more ambient particulate matter samples (receptor profile) are used to calculate the proportionate contribution of each source to the corresponding receptor sample.

RESULTS AND DISCUSSION

General Features

The results of the above analyses and modelling techniques were used to characterize the particulate matter and determine its major sources. The characteristics of the data may be summarized as follows:

- Observed TSP levels were log-normally distributed and consistent from site to site, indicating that the Experimental and Control sites were similar in character, and that the TSP levels were the result of relatively large scale influences rather than specific predominant sources
- Consistent daily variations were observed in TSP levels, the most probable causes being diurnal variations in wind speed, source emission rate, and traffic volume
- At the Cannon St. sites, the highest TSP levels occurred when winds were out of the northeast reflecting the combined impact of emissions from the industrial sector and urban area, whereas

for the School and Stelco Reseach Centre sites, highest levels occurred when winds were out of the southwest, reflecting the impact of both local highways and industry

- Height and distance profiles of TSP levels relative to the roadway show clearly the contribution of reentrained road dust
- Size specific particulate data show that the fraction having an aerodynamic diameter of less the 15 μm comprises approximately 45% of TSP, while the fraction less than 2.5 μm represents approximately 22% of TSP
- The results of chemical and morphological analysis show directional patterns consistent with the observed effect of wind direction on ambient particulate matter levels, and exhibited anticipated source contributions.

Source Apportionment

Three different methods were used to determine the average percent contribution of various source categories to TSP levels in the downtown Hamilton area. The source categories used were as follows:

Area: fugitive dust sources such as unpaved parking lots, construction sites, and small point sources such as residential heating, railway yards and incinerators

Point: major point source emissions in and around the area. This is primarily the steel industry component

Traffic-related: includes both reentrainment road dust and direct vehicular emissions from all streets in the study area

Background: includes the long-range transport component and other unidentified sources beyond the study area

Unexplained: that portion of the TSP levels not apportioned to one of the above source categories by the methods employed. The background term in both the microinventory and dispersion modelling approaches is a residual term and so there is no unexplained portion in these cases.

The results of the three methods can be summarized as follows:

Source	Percent Contribution		
	Microinventory	Chemical Mass Balance	Dispersion Model
Area	16 - 2	3	19
Point	2 - 17	8	6
Traffic-Related	43 - 27	34	40
Background	34 - 54	30	35
Unexplained	-	25	-

The ranges of values provided for the microinventory represent the results obtained using two different approaches. In the first instances, an equation based upon studies in several U.S. cities was used to evaluate TSP levels in Hamilton in terms of the microinventory for the study area. In the second instance, the TSP monitoring results were used to derive a Hamilton - specific relationship. Despite the diversity of the approaches used, a quite consistent apportionment of the source categories results. The largest contributor to TSP levels during the study period was traffic-related. The average contribution was about 40%, of which road dust reentrainment accounted for 30% and vehicular exhaust 10%.

The background contribution is the least well-defined of the four source categories. In both the microinventory and dispersion modelling, this factor arises as a residual term, determined primarily by the monitoring results for the three background sites. However, the average figure of ∿ 35% is in good agreement with the results of other studies specifically concerned with the determination of background TSP levels in Hamilton and elsewhere. The CMB background estimate of 30% represents only the sulphate component expressed as ammonium sulphate. Other chemical constituents such as organic matter, metals and nitrates, are known to be present in background aerosols. The CMB analysis accounts for ∿ 75% of the total particulate mass. The unexplained 25% would be distributed amongst the four categories, but about one-half (12%) can be attributed to the background components.

The area sources were determined to contribute ∿ 10% of the airborne particulate matter. This source is somewhate larger than the point source contribution of ∿ 7%. Thus, despite their obvious impact under certain meteorological conditions, point sources appear to have contributed a relatively small fraction, on average, to the total observed particulate matter burden at the Experimental site during the study period. These results are considered to be representative of the central urban area during this period. However, the relatively infrequent occurrence of poor dispersion conditions during the study period should be noted.

An analysis of individual sampling periods and their related meteorological regimes during the study indicates that the percent contribution of the iron and steel CMB component was particularly dependent upon wind direction. The other major components did not show a significant dependence upon wind direction, on average. As expected, the iron and steel CMB component made a larger contribution when the wind blew from the industrial sector to the Experimental site. The relative contribution of the iron/steel component to the inhalable particulate mass was as high as 22% during an individual sampling period.

This summary represents a condensation of the results obtained by the three independent methods used to apportion the observed particulate loadings to the four source categories. Each of the methods has strengths and weaknesses and these are discussed in the report. The above summary is the most reasonable scientific interpretation of the results and their agreement with each other allows considerable confidence in the conclusions.

These results also should be considered in the perspective of the significant improvement in air quality achieved in Hamilton over the past ten years. Industrial emissions have been reduced by 71% during this period, resulting in reductions of ∿ 40% in the city averages for TSP and coefficient of haze measurements. Attention continues to be given to the abatement of emissions from the remaining major uncontrolled sources within the Hamilton steel mill complex. However, considering the high density of industry in close proximity to the urban area, the unavoidable occurrence of inversions, and the demonstrated significance of emissions from general urban activies and background contributions, it is unlikely that unsatisfactory air quality for short-term occurrences can be completely avoided in Hamilton in the near future.

Street Sweeping Assessment

Street sweeping on a regular schedule is a main component of most urban street maintenance programs. The ability of street sweepers to remove accumulated dust and debris from the street surface is well documented, and the aesthetic value and desirability of such programs is apparent. However, the effectiveness of street sweeping as a control measure for the reduction of ambient TSP levels is not well defined. In this study, the effectiveness of more frequent application (daily instead of weekly) of both mechanical and vacuum sweepers of conventional design was evaluated, with special emphasis given to the establishment of reference conditions so as to allow for contributions from other sources. The higher loadings occurring during the mechanical sweeping period as compared with the baseline period can be attributed to factors other than the increased frequency of sweeping and all features of the TSP data indicate no statistically significant difference in TSP levels during this period. The geometric mean TSP level for the vacuum sweeping period shows a decrease of 7%, and statistical tests indicate that this decrease can be considered marginally significant. The modelling results can be interpreted to support this conclusion. However, a statistical evaluation of the data for specific sets of conditions which were expected to provide a more sensitive test of the impact of reentrained road dust on TSP levels showed no significant difference between the Experimental and Control sites. Receptor modelling (chemical mass balance) results showed a small but significant decrease in the relative contribution of the road dust component during vacuum sweeping, and a small increase with mechanical sweeping. The dispersion modelling results indicate that a substantial reduction ($\sim$ 30%) in the road dust contribution would have to be realized in order to result in the 7% TSP reduction observed during the vacuum sweeping period. Thus, although an increased frequency of vacuum sweeping may have resulted in a small decreased TSP levels, more frequent sweeping of roads and streets is unlikely to be an effective approach to the control of airborne particulate matter in most urban areas unless undertaken as part of a comprehensive program which addresses all significant source categories.

Methodology Assessment

Both the experimental and data analysis components of the study were quite broad in scope so that the different approaches available for use in such studies could be evaluated and recommendations made for their future use. Most of the components of the Hamilton study proved relevant to the objectives and goals defined at the outset of the program. The experience gained can be used to define more specific studies which might be required in the further development of particulate matter control strategies. In designing such studies, the relative merits of long and short-term studies must be assessed in terms of the specific requirements at hand. TSP monitoring, particle size measurements, basic meteorological measurements, and selective chemical analysis of the collected samples are likely to be desirable components of most studies. A comprehensive evaluation of the general features of the data should be a well-defined component of the study and the results can be used to determine more specific assessments to pursue. The preparation of a micro-inventory of sources, dispersion modelling and receptor modelling are specific approaches which can be used to make source apportionments. Receptor modelling is a recently developed method which has proven to be a practical and versatile tool for the quantitative assessment of the relative importance of different source categories. The merits of each method must be assessed relative to the data base available and the specific needs of the study.

1. INTRODUCTION

Over the last decade, control strategies with emphasis on traditional industrial sources of particulate matter have achieved a substantial reduction in suspended particulate matter concentrations in the ambient atmospheres of a number of cities with heavy industries within their boundaries. However, there appears to be a limit to the improvements in this component of air quality which can be achieved through control of these traditional sources. Analysis of trends in total suspended particulate (TSP) matter levels observed in urban atmospheres during this period indicates that, despite continuing abatement efforts by industry and government, TSP air quality objectives in urban areas may not be realized through control of traditional sources alone.

To illustrate this problem of meeting the particulate matter air quality criteria in urban areas, air quality data for the City of Hamilton may be used. Hamilton is an industrial city with predominantly heavy steel and chemical industries. According to the Ontario Ministry of the Environment, the TSP levels for Hamilton, as measured at 7 sites, averaged 131 $\mu g/m^3$ in 1970. This average was reducted to 74 $\mu g/m^3$ by 1977, reflecting a remarkable achievement in TSP air quality achievement in TSP air quality improvement. At the same time, point source particulate emissions were reduced from 63.0 to 22.5 million lbs/year at a cost of $72 million. It has been stated that another $80 million would be required for further reduction of emissions to 14 million lbs/year, and it has been estimated that this expenditure would produce a lowering in TSP levels of approximately 8 $\mu g/m^3$.

Several major studies have been conducted over the past few years to investigate the urban TSP problem. Some of them have been concerned with identification of suspended particulate constitutents; others were directed towards the evaluation of various control techniques and strategies. Most of the studies were very narrow in scope and overlooked some very important aspects of the overall urban particulate matter problem. In most instances, the quantification of contributions by various sources has been attempted without allowing for the effect of such key independent variables as meteorology, traffic parameters, urban characteristics, background levels, and industrial activity. However, while the results of each individual study taken alone are inconclusive, the preponderance of evidence leaves little doubt that resuspension of deposited particles makes a substantial contribution to urban TSP levels, and this is a significant limitation in the attainment of TSP air quality objectives in urban areas.

These problems of non-attainment can only be addressed by considering all sources contributing to TSP. Knowledge of the relative importance of the various source categories can then be used to develop an effective particulate control strategy for urban areas.

This study of urban road dust and other sources of suspended particulate matter was undertaken to provide technical and scientific information which can be used to develop comprehensive and effective urban particulate matter control strategies in Canada.

The study was carried out in Hamilton, Ontario. This city was chosen because it affords the right balance of heavy and light industry, residential and commercial development, and adjacent rural environments to assess the effects of most of the identified sources of particulate emissions. The specific objectives of the study were:

(i) to develop a better understanding of the predominant factors determining particulate matter concentrations in the City of Hamilton. In order to meet this objective, the following specific goals were defined:

- to characterize the physical and chemical composition of individual size fractions of urban particulate matter
- to identify major source categories of urban particulate matter and quantify their contribution to ambient levels
- to determine the effect of major independent variables such as meteorology, traffic patterns, and urban characteristics on the extent of particulate matter reentrainment
- to evaluate currently used street sweeping methodologies.

(ii) to use the above results to define a suitable methodology for the development and evaluation of particulate matter control strategies for urban areas on a nation-wide basis.

2. BACKGROUND

2.1 Airborne Particle Measurement and Analysis

There are many, good recent reviews of airborne particulate matter measurement methods (1-7). Only points that are especially relevant to this study will be highlighted here. This section begins with a very brief historical summary of the development of particulate matter sampling instrumentation. Current reference or standard methods are described briefly. Instrumentation and methods for collecting size-fractionated samples of airborne particles are also discussed.

Although the Hamilton Study did not include specific source emissions measurements, data from such measurements are referred to in various places in this report; therefore, a summary of source measurement methods is given. Methods for analyzing the chemical composition and physical characteristics of particulate matter are integral parts of measurement methodology. An outline of analysis methods is, therefore, included in this section.

2.1.1 Sampling Instrumentation

Various principles have been applied to the development of instruments for collecting airborne particles. The sampling techniques can be classified into four main categories: filtration, inertial separation, radiation extinction and electrostatic or thermal precipitation (2). The latter technique has not been applied extensively to ambient particulate matter and will not be discussed here.

Filtration was the first widely applied method of ambient air particulate sampling. The so-called high volume sampler (HiVol) is a filtration device whose development in the early 1950s led to systematic measurements of airborne ambient particle loadings in Britain and in North America. The HiVol, in its simplest form, consists of a filter holder and an air pump (typically a centrifugal blower) capable of drawing approximately 100 cubic meters of air per hour through a fibrous matte filter. Particles are collected by impaction on the filter surface. The particle mass concentration can be determined by weighing the quantity of material deposited on the filter and dividing this value by the volume of air sampled. Concentration is expressed typically in micrograms per cubic meter of air. The collection medium - the type of filter material - clearly may influence the physical and chemical integrity of the collected sample. Filter media are discussed below.

The mass collected by the HiVol sampler is variously referred to as suspended particulate matter (SP) or total suspended particulate matter (TSP). These terms refer generally to particles that would remain airborne for periods of the order of several hours to several days after being entrained by natural or anthropogenic forces. The housing in which a HiVol sampler is operated is usually designed so that only particles having effective aerodynamic diameters smaller than approximately 30 micrometers are collected (8). It should be noted at this point, that aerodynamic properties of particles depend upon their shape and density as well as their size. Discussions of airborne particles, including this report, usually use effective or equivalent aerodynamic diameter to refer to the diameter of a hypothetical sphere of unit density that would be collected by a given sampler design. Real sampled particles will have sizes that differ from the nominal value because of their different densities and shapes. The nominal cutoff diameter usually refers to the median number of particles sampled. That is, the cutoff diameter is that for which 50% of the particles are collected and 50% rejected by the sampler inlet. Particles larger than this size would normally settle out of the atmosphere rapidly, except under the influence of strong winds. This cutoff is very approximate and depends upon the sampling flow rate, the shape of the housing and the wind speed. Filters on a HiVol sampler are changed manually, which means that operation is labour intensive, but the simplicity of its construction, ease of operation and relatively low cost have made the HiVol sampler predominant in the field of ambient airborne particle sampling during the past thirty years. The most common design is used throughout North America.

Other than having an approximate 50% cutoff at 30 micrometers, which depends on wind speed, the HiVol does not further fractionate airborne particles according to size. Attachments for the HiVol are available that fractionate TSP into several size categories. The most commonly used attachment is the cascade impactor (2,3). This device exploits the inertial and aerodynamic properties of particles accelerating through a series of jets to separate the larger particles in stages into descending size fractions by impaction onto collection surfaces. The smallest particles (less than about 1 micrometer in equivalent aerodynamic diameter) are collected on a standard HiVol back-up filter. Five size fractions of airborne particles are commonly obtained in this way.

The portion of suspended particulate matter that is capable of entering the human respiratory system is determined by the inertial and aerodynamic properties of the particles. Data on the size distribution of ambient particles therefore, are of interest in assessing the effects of suspended particulate matter. Even so, the amount of systematically accumulated data on size fractionation of ambient particles is relatively meagre. There is also a low-volume seven-stage version of the cascade impactor which has been used for ambient measurements.

TSP samples for chemical and physical analysis traditionally have been collected by the high volume method because the instrumentation collects a sufficiently large quantity of particulate matter to permit physical and chemical composition to be determined with reasonable accuracy.

Other Traditional Particulate Matter Sampling Methods. Two quantities other than SP & TSP that have been used as indicators of atmospheric particulate matter loading for many years are coefficient of haze (COH), or soiling index, and dustfall.

COH is measured by the darkening that airborne particulate matter causes when collected on a filter medium. Most commonly, ambient air is drawn by a pump at a relatively low flow rate through a filter tape that is automatically advanced after a specific interval. The density of the particle deposit on the filter is measured by the attenuation of a transmitted beam of light. The concentration of particles in the sampled air volume is expressed in terms of the relative darkening of the filter paper as dimensionless COH units (9).

The sampling inlet and flow rate of the COH instrument are designed such that only particles less than about 5 to 10 micrometers in diameter are collected on the filter tape.

The coefficient of haze or soiling index is a relative measure of atmospheric particulate matter loading and does not determine the mass concentration directly. It is useful as a semi-continuous indicator of small particle loading, and it has been used successfully as an indicator of airborne particle loading as a component of Ontario's Air Pollution Index (10).

The British Smoke Shade sampler is similar in operating principle to the COH instrument, except that relative filter darkening is determined by attenuation of light reflectance rather than transmittance.

Dustfall is a general indicator of atmospheric loading of larger particles that settle out or that are washed out of the air by precipitation. Dustfall is defined as the quantity of solid matter that falls passively into an open container of specified dimensions. Its mass is determined gravimetrically after filtering from any collected precipitation and drying. There are no pumps or other moving parts in a dustfall collector. Although the measurement is not particularly informative, dustfall collectors have the advantages of extreme simplicity and low cost. The quantity of dustfall is usually expressed as tons of dustfall per square mile per month, or grams per square meter per month.

Inhalable or Respirable Particulate Matter Sampling Methods. For many years, the American Conference of Governmental Industrial Hygienists (ACGIH) has defined a size classification of "respirable dust", meaning that portion of dust that is inhaled and that can reach the pulmonary region (2,6). The nominal median particle diameter of the ACGIH "respirable dust" is 3.5 micrometers. This criterion is normally applied to airborne dust sampling in industrial hygiene measurements. Only recently has an attempt been made in North America to define a standard size classification for sampling ambient airborne particles (11-15).

The U.S. Environmental Protection Agency (EPA) tentatively has defined "inhalable particles" (IP) as those particles that are smaller than 15 micrometers in diameter, which includes particles that are deposited predominantly in the upper region of the respiratory tract (conducting airways) during normal nasal breathing and those that may reach the lower (gas exchange) region of the lung during mouth breathing. EPA defines "respirable particles" (RP) as those having effective aerodynamic diameters less than 2.5 micrometers. The latter size has physiological significance (compare the ACGIH value, 3.5 micrometers) but was also chosen because it has physical significance with respect to the typical size distribution of suspended particles in the atmosphere. There are normally relatively few particles in the atmosphere with effective aerodynamic diameters of about 2.5 micrometers. This diameter, then, effectively demarcates a "fine particle" fraction from a "coarse particle" fraction.

Two instruments have been designed to EPA specifications to address the sampling of particles in the above-designated size ranges (IP and RP). These instruments are the dichotomous sampler, for IP and RP, and the size-selective inlet (SSI) attachment for the standard HiVol (IP only).

The dichotomous sampler was developed under the sponsorship of EPA during the early 1970's (16). As its name implies, it separates the sampled aerosol into two size fractions by means of a single-stage virtual impactor. Particles in the separated fractions ("fine" and "coarse") are collected on matte or membrane filters. The impactor is called "virtual" because the particles do not impinge upon a collection surface immediately after being accelerated through the inlet air jet, but instead, pass through a void (virtual surface) and are collected by filtration downstream. The air flowrate is about 10 times greater in the fine fraction collector than in the coarse particle collector. Simply put, the separation is achieved because the coarse particles are unable to follow the streamlines of the air path and pass into the low flowrate branch of the impactor, while the fine particles are able to follow the streamlines and are diverted into the high flowrate branch. A relatively sharp cutoff between the fine and coarse fractions is achieved by the design of the inlet and impactor head, combined with the air flowrates in the two branches.

The size selective inlet (SSI) attachment for the HiVol sampler is designed to sample the IP fraction of airborne particulate matter, that is, particles smaller than 15 μm in effective diameter. This sampler is operated in essentially the same manner as a standard SP/TSP HiVol. The modified inlet better defines the size fraction of particles collected by the sampler and is designed so that wind direction does not influence the sampler's collection efficiency.

Both the dichotomous sampler (in manual and automated versions manufactured by several suppliers) and the SSI HiVol are being deployed in a so-called inhalable particulate network by EPA in the U.S. In 1979/80, 97 sites in 39 cities were to be equipped with various combinations of dichotomous samplers, SSI HiVols and SP/TSP HiVols (17).

Other Size-Classifying Particle Samplers. The previous sections have described the principal samplers that have been used extensively in systematic network sampling programs for airborne particles. Many other samplers and measuring instruments have been used over the years to determine atmospheric concentrations and other characteristics of aerosol particles. Good summaries of these instruments appear in references (2) and (3). A few of these will be mentioned briefly here.

As discussed above, the ACGIH has defined respirable dust as a specific size fraction of airborne particles. There is a recommended method for sampling this fraction that involves the use of a small cyclone particle selection stage in front of a membrane or other type of filter. The cyclone is another type of inertial separator that traps particles larger than a nominal effective diameter, that cannot follow the streamlines of the abruptly changing direction of the air stream, and allows particles smaller than that diameter to pass through to the collection medium. Such devices have been used mainly in occupational hygiene applications but have also been used to define the size fraction collected by ambient air particle samplers.

Various other types of impactors, precipitators and sedimentation devices have been applied to special studies of the nature of ambient air aerosols, but these will not be discussed here.

Instruments that measure properties of aerosol particles in situ have also been used extensively in aerosol characterization studies. Many of these devices depend upon optical or electrical properties of particles to determine their mass, number or volume concentration and size distribution in continuously or semi-continuously sampled air streams. They are not useful for determining properties other than those just mentioned. Specifically, samples suitable for chemical or physical analysis are not collected. See references (2) and (3) for additional information on these instruments, which include the integrating nephelometer, the electrical mobility aerosol analyzer, optical particle counters, and condensation nuclei counters.

An intercomparison of various ambient particle samplers has been sponsored by the U.S. EPA (18).

2.1.2 Source Particle Measurements

All airborne particles originate from some source, which may be natural or anthropogenic and may arise from primary emissions or secondary atmospheric reactions. All of the measurements of airborne particles that were undertaken for the Hamilton study were of ambient air. Measurements of emission from specific sources of the airborne particles were not made. Nevertheless, it is appropriate to mention briefly the methods that are used to sample emitted particles at the source, because these methods are different from ambient air methods and because data based on source measurements are referred to later.

The term "source measurement" normally refers to stationary (as opposed to mobile) combustion sources and industrial process sources at which measurements are made in stacks or vents before the pollutants (e.g., particles) enter the atmosphere. In this type of measurement, one determines the "source strength", that is, the rate of emission, which is typically expressed as mass per unit time (e.g., kg/h). The brief discussion that follows will be limited to those methods which extract samples of emitted particles from flue gas, although *in situ* monitoring devices for particles in flue gases are widely used. Chemical characterization is currently possible only for extracted samples.

Special source measurement methods are necessary, because, compared to ambient air, flue gases are usually hot, moist, densely laden with particles, are moving at high velocity, and are sometimes corrosive. All of these conditions present sampling problems.

The most critical parameter from the point of view of sampler design is the particle velocity. Unless the sampler inlet velocity matches the flue gas velocity, a non-representative sample of entrained particles will be collected, and the measured particle concentration will be different from the actual flue gas concentration. Particulate matter in flue gases, then, must be sampled under so-called isokinetic conditions. Means of achieving isokinetic sampling are specified in detail in the Ontario Source Testing Code, (19) and by Environment Canada (20), along with other requirements for achieving a representative sample under various conditions in stacks or vents.

Source sampling trains may be outfitted with various attachments to achieve particle size fractionation. The most commonly used devices are cascade impactors and cyclones, designed specifically for this application.

Collected source samples can be analyzed chemically and physically in essentially the same ways as ambient samples. The discussion of analytical methods that follows applies equally to source and to ambient samples.

2.1.3 Standard or Reference Sampling Methods

The intent of this section is not to provide details of standard or reference sampling methods but to list the various methods and to indicate where more details may be found.

Ambient Air Sampling Methods for Particulate Matter. The Canadian federal reference method for sampling suspended particulates has been published by the Environmental Protection Service of Environment Canada (21). This method specifies the conditions under which the HiVol sampler is to be operated, along with quality control precautions. An analogous Ontario method also has been described (22).

The U.S. Federal Reference Method for sampling suspended particulate matter is very similar to the Canadian methods referred to above. It was published in the U.S. Federal Register (Vol. 36 (84), pp. 8191-8194) in 1971. Additional specifications for sampling networks and siting criteria appeared in the Federal Register (Vol. 43 (152), pp. 34924-34926) in 1978, under the title "Air Quality Surveillance and Data Reporting".

Standard methods for both dustfall and COH have been published by the American Society for Testing and Materials (ASTM). Standard method D1739-70 refers to dustfall and standard method D1704-78 refers to soiling index (COH). These methods with any revisions are published in the ASTM Annual Book of Standards "Sampling and Analysis of Atmospheres", currently designated as Part 26 (23). These ASTM methods are used commonly by air pollution regulatory agencies and industry. Other reference methods for all of the above parameters have also been published by the Intersociety Committee (ISC) (24).

ASTM standard methods for determining particle size distribution in ambient air by filtration (Method D2009-79) and liquid-filled impinger (Method D3365-77) have been published (23), but neither is based on current technology.

The Intersociety Committee Manual specifies a multi-stage cascade impactor for the determination of particle size distribution (24). In addition, the ISC give methods for light scattering aerosols and visibility (24).

Stack Sampling Methods for Particulate Matter. The Canadian federal method for sampling particulate in stacks is given in an Environment Canada, Environmental Protection Service report (20) entitled, "Standard Reference Methods for Source Testing: Measurement of Emissions of Particulates from Stationary Sources".

Both the Canadian and Ontario reference stack (i.e., stationary source) testing methods are similar to the U.S. EPA Federal Reference Method Number 5 (25). Details of these methods will not be given here, because the specifications differ significantly from one source type to another. The methods involve specifications for positioning the sampling probe, placement of particulate filters (whether inside or outside of the stack), flowrate control, temperature control, impinger design and absorbing solutions, and the number of samples to be collected for statistical significance, for example.

2.1.4 Chemical Analysis of Particulate Matter

Once a representative sample of airborne particulate matter, or a well-characterized fraction thereof, has been collected and a means of maintaining the integrity of the sample on its way to a laboratory has been established, there are many analytical methods that may be used to determine the chemical composition of the sample. The analysis step is essential to determine the concentrations of potentially harmful elements and compounds collected in an ambient sample. The latter is possible if the chemical composition of particles emitted from specific sources is known, which can be determined, of course, from the analysis of source and process samples.

Essentially all methods of chemical analysis, both manual and instrumental, have been applied to the analysis of airborne particulate matter. Those methods that were used in this study are discussed briefly below. Details of these methods and of the many other methods that are not mentioned may be found in reference texts on laboratory analysis (5,26,27).

Destructive Elemental Analysis Methods. Traditionally, samples of airborne particles have been analyzed by methods that required the particle matrix to be broken down, usually dissolved, before analysis. Most samples are still analyzed by destructive means, and a significant portion of the chemical analysis data generated in this study were obtained by such means.

The most common method of dissolving particulate matter prior to multi-element analysis is acid digestion. This treatment releases elements (as ions) and their counter ions into solution. Since airborne particles consist of such materials as minerals and glassy combustion fly ash, the particle structure (the so-called matrix) is often difficult to break down, and the dissolution step is critical in the analytical protocol. Attention was given to this potential problem in the study.

Both flame-source and flameless atomic absorption spectrometry (AA and FAA, respectively) were used in this study. Generally, AA involves heating an aliquot of the sample solution quickly in a reducing flame to release the components as elemental vapours. The concentration of an element in the sample is determined from the attenuation of a light beam at a wavelength that is specific to the element. The light source is usually a discharge lamp containing the target element, which emits light at discrete wavelengths characteristic of the element. The measured amount of light absorbed by the element in the atomized sample is related to the quantity of the element present in the sample.

FAA is very similar in principal to AA, as described above, except that the sample aliquot is introduced into a furnace that vaporizes it and releases the components. The light sources and detectors are essentially identical to those used in flame source AA. AA and FAA have sufficient sensitivity for most elements of interest down to levels that correspond to background concentrations in typical sample quantities.

Aqueous extracts or digests of particulate matter can be analyzed for anions and cations by ion chromatography (IC). This method relies on differential retention of ions on an ion exchange column to separate the components of the sample. An aliquot of the sample solution is injected onto an ion exchange column and eluted by a specific carrier solution. The separated components are detected by changes in conductivity of the eluent as the individual types of ions elute from the column. The output of the electrical conductivity detector is related to the quantity of analyte present in the sample.

IC has become an increasingly important means of analyzing samples of airborne particulate matter, especially for sulphate, nitrate and the halide ions. IC was used to analyze for these species in aqueous extracts of various types of particulate matter samples collected during the Hamilton study.

Non-destructive Elemental Analysis Methods. There are several multi-element analysis methods that do not require the particulate matter matrix to be dissolved prior to analysis and that in principle do not affect the integrity of the sample. Two such methods that were used on the particulate samples collected during the Hamilton study were instrumental neutron activation analysis (INAA) and X-ray fluorescence spectroscopy (XRF). Both methods are capable of multi-element analysis of particulate samples directly on the filter collection medium. This capability alleviates time-consuming sample preparation and, in principle, leaves the sample intact for subsequent analysis by other techniques or for archiving (1,28).

INAA involves bombarding the sample with a stream of neutrons in a nuclear reactor. The atomic nuclei of the various elements in the sample absorb some of the neutrons and are excited to unstable higher energy states. As the nuclei relax to their stable forms, emissions of energetic photons or particles take place. The beta and gamma-rays that are given off have energies and decay times that are characteristic of the nuclei that were excited. The intensities of beta or gamma-rays given off by the sample are proportional to the quantities of excited elements present. The INAA technique, then, involves measuring the intensities and characteristic energies of the radio-active emissions to determine the amount of each element in the sample. There are some elements that are not accessible by this method, since their nuclei are not exited or are only weakly excited by neutron irradiation, but most elements of environmental interest are measurable with good to excellent sensitivity.

Because of the high energy of excitation compared to normal chemical energies, INAA is not very prone to errors or interferences due to the chemical form or particle structure in which the elements are found in the sample.

The main limitations of INAA are practical ones: relative inavailability of nuclear reactors, sample handling requirements due to the radioactivity of the irradiated sample, and the specialized knowledge required to conduct the irradiation and interpret the results. Fortunately, there is a group at McMaster University in Hamilton, experienced in the use of INAA on airborne particulate matter samples at the University Nuclear Research Centre, and who were available to work on the study samples. INAA has been applied previcusly to the analysis of bulk road dust material (29).

XRF has not been applied extensively to the multi-element analysis of airborne particulate matter in Canada, although it has been used both in the U.S. and Europe. There are two basically different types of spectrometers that are used for XRF analysis: wavelenght-dispersive and energy-dispersive. Each is based on the principle that atoms can be excited to emit characteristic X-ray radiation (fluorescence) after absorbing X-rays of equal or greater energy from an excitation source.

In wavelength-dispersive XRF, the emitted X-rays are sorted according to their wavelengths by a refracting prism. Each characteristic X-ray is brought onto the detector by rotating the prism (the dispersive element) through the necessary angular adjustment. The X-ray intensity (number of X-ray photons per unit time) at a given wavelength is proportional to the number of atoms of the corresponding type in the target sample. In normal usage, the requirement that the dispersion element be rotated to accommodate each element sought means that the elements in a given sample must be analyzed in sequence. This procedure is relatively time consuming, since the detector signal for each element normally needs to be processed for a few minutes before the next element's wavelength is positioned.

Energy-dispersive XRF depends solely upon the response of the detector to resolve the characteristic X-ray emissions of the excited atoms in the sample. This means that the information contained in the emitted X-ray beam is processed by the detector simultaneously for the entire group of elements excited by a given X-ray source. The beam intensity at each characteristic energy is again proportional to the number of the corresponding atoms in the sample.

Energy-dispersive XRF is inherently rapid because of the simultaneous processing of signal information for many elements. Energy-dispersive XRF has had problems with resolving certain elemental emissions from one another compared with wavelength-dispersive XRF. Recent developments in source design and signal processing have alleviated many of the more serious deficiencies of the energy-dispersive versions (28,30).

Both types of XRF must make use of several secondary X-ray sources to cover the desired range of elements. That is, the primary source in the XRF instrument serves to excite secondary X-ray fluorescence from one of several targets made of different metals. The secondary X-rays then excite X-ray fluorescence in the particulate sample. This arrangement optimizes the sensitivity of the instrument for a large number of elements.

XRF is susceptible to particle matrix effects and sample geometry effects. Sample geometry can be controlled by collecting the sample on an appropriate filter. Matrix effects can be alleviated in part by ensuring that the filter loading is not too heavy, but an effect due to particle size (reabsorption of fluorescent radiation by large particles themselves) is a more difficult problem.

Other Methods of Chemical Analysis. Many studies of airborne particulate matter have utilized analysis of an organic solvent extract to identify several hundred organic compounds that are (mainly) adsorbed on airborne particles (31, 32). Gas chromatography (GC), gas chromatography combined with mass spectrometry (GC-MS) and thin layer chromatography (TLC) have been used extensively to identify particulate organic compounds. The data on organic compounds are not systematic enough, however, to aid in identifying specific air pollution sources, except in special cases. Therefore, samples collected during this study were not subjected to analysis for organic compounds.

Some samples were analyzed for volatile and non-volatile carbon, the former being a measure of the organic (plus carbonate) fraction of particulate matter. The carbon analysis was carried out by an innovative technique developed by Professor James Huntzicker at the Oregon Graduate Center over the past several years (33). The technique is described in some detail in Section 3. Generally, volatile carbon in the sample of particulate matter on the original filter is analyzed by pyrolyzing the sample in a helium atmosphere, catalytically oxidizing the carbon compounds thus evolved to carbon dioxide and measuring the carbon dioxide. The non-volatile portion of carbon in the sample is liberated by introducing oxygen to the pyrolysis chamber. The oxygen oxidizes the remaining carbon to carbon dioxide, which is measured as for the volatile portion. The non-volatile carbon so determined is a measure of the graphite-like and other stable forms of carbon produced mainly by combustion sources.

Physical Methods of Particle Characterization. Physical properties of airborne particles are also useful in determining their sources and understanding their effects. The most important methods for determining physical properties of airborne particles are the various types of microscopy. The applications of microscopy to studies of particulate matter have been described in detail by McCrone (34) and Draftz (35,36) and will be discussed only briefly here.

The two types of microscopy that are used to examine airborne particle samples are polarized light microscopy (PLM) and electron microscopy - either the scanning electron microscope (SEM) or the transmission electron microscope (TEM).

The polarized light microscope is used to examine particles as small as one micrometer in size. PLM is used to determine morphological and optical properties and crystal structure of particles that often can assist in identifying their composition and source. Very little sample preparation is required, so that PLM examines particles essentially *in situ*, that is, in the state in which they were sampled (37,38).

SEM and TEM can be used to examine particles as small as a few hundredths of a micrometer but the sample preparation required usually means that particle form is modified somewhat from that in which it was sampled. Because of the nature of the electron microscope image, only particle morphology can be determined

An attachment that enables the SEM to provide elemental chemical analysis of individual particles is the electron microprobe. Briefely, this device bombards the particle with a beam of electrons that excite X-ray fluorescence from the particle which can be detected and processed in a way that is qualitatively similar to XRF spectroscopy (see above).

This brief presentation of particulate matter measurement methodology could only provide a rudimentary introduction to this complex and highly developed field. Selection of subject matter was influenced heavily by the choice of methods for this study.

2.2 Air Quality Trends For Particulate Matter

During the past 20 to 30 years, measured ambient suspended particulate matter levels have declined significantly in North America. This trend has resulted from a joint effort on the parts of air quality managers in regulatory agencies and in industry to identify sources of emissions and to control them. This section begins with a summary of North American ambient air quality standards, objectives and criteria. These values serve as the benchmark for comparing ambient air measurements of particle concentrations and associated trends, both generally and for the Hamilton study in particular.

2.2.1 Ambient Air Quality Standards, Objectives and Criteria

Ambient air quality standards (designated by various names in various jurisdictions) have been promulgated under the Canadian Clean Air Act, the Ontario Environmental Protection Act, and the U.S. Clean Air Act.

The Canadian Federal standards are called National Ambient Air Quality Objectives (NAAQO's) (39). For suspended particulates, the Canadian NAAQO's are as follows:

Averaging Time	Maximum Desirable Concentration	Maximum Acceptable Concentration	Maximum Tolerable Concentration
Annual (geometric mean)	60 $\mu g/m^3$	70 $\mu g/m^3$	-
24-hour	-	120 $\mu g/m^3$	400 $\mu g/m^3$

The annual geometric mean is the average of individual 24-hour values.

The analogous Ontario standards are known as Ambient Air Quality Criteria. The Ontario annual criterion for suspended particulate matter (TSP) is 60 $\mu g/m^3$ (geometric mean as above) and the 24-hour criterion is 120 $\mu g/m^3$. There are no equivalent standards in Ontario to the federal annual "maximum acceptable concentration" or the 24-hour "maximum tolerable concentration".

The corresponding standards in the U.S. are called National Ambient Air Quality Standards (NAAQS's). For total suspended particulate matter (TSP), the U.S. NAAQS's are:

Averaging Time	Primary Standard	Secondary Standard
Annual (geometric mean)	75 $\mu g/m^3$	60 $\mu g/m^3$
24-hour (not to be exceeded) more than once a year	260 $\mu g/m^3$	150 $\mu g/m^3$

The primary standards are levels that are judged to allow an "adequate margin of safety" and "are requisite to protect the public health". The secondary standards are levels that are judged to be "requisite to protect the public welfare from any known or anticipated adverse effects associated with the presence of air pollution".

These standards are all based on inferences from the human health literature about levels at which effects may occur. These effect levels are generally referred to as "criteria" in the air pollution literature. The standards then, are chosen to represent levels below the "criteria" levels.

The values listed above differ somewhat from jurisdiction to jurisdiction for several reasons, but they are all judged to represent air quality that will not be injurious to human health. The differences arise because of legitimate and defensible variations in parameters such as sampler siting criteria, sampling frequency, statistical treatment of data and interpretation of historical data on which effects criteria are based.

Ancillary Indicators of Air Quality for Particulate Matter. Ontario has promulgated ambient air quality criteria for dustfall and soiling (index) in addition to TSP. The criterion for dustfall is 20 tons/mi^2/mo (total accumulation over 30 days) or 13 tons/mi^2/mo averaged over one year (average of 30 day values). Expressed in metric units, the corresponding values are 7.0 g/m^2/30 days or 4.5 g/m^2/30 days averaged over one year, respectively.

For soiling index, expressed in coefficient of haze units, the corresponding values are 1.0 COH/1,000 ft. of air sampled, averaged over 24-hours or 0.5 COH/1,000 ft. of air sampled, averaged over 1 year (average 24-hour values).

2.2.2 Trends in the United States

In the United States, the National Air Surveillance Network (NASN) was established to monitor ambient particulate matter concentrations. This network began in 1957, consolidating a number of local, state and federal monitoring sites. It was systematized in the late 1960's and early 1970's, eventually under the purview of the Environmental Protection Agency as the National Aerometric Data Bank. The data produced by this network indicated that between 1970 and 1974 annual geometric mean TSP concentration measured by the HiVol reference method for 1014 urban sites declined from 81 to 68 $\mu g/m^3$ (40,41). That is, overall the network sites were in compliance with the primary annual standard of 75 $\mu g/m^3$. Many Air Quality Control Regions (AQCR's), however, had one or more sampling sites that did not attain the primary annual standard. Furthermore, between 1974 and 1977 (41), TSP as measured in the NASN did not continue to decline at the same rate as in the previous 5 years, and many AQCR's were still not attaining the primary standard. Indeed, during the period 1970-1977, nationwide particulate matter emissions were estimated to have decreased by 50% (referring mainly to industrial stationary sources), whereas TSP levels across the whole NASN (all sites, urban and rural) decreased by only about 8% (41). As of 1978, many AQCR's were still not attaining the primary National Ambient Air Quality Standard and the network annual mean was still above the secondary annual guideline of 60 $\mu g/m^3$. Some caution should be exercised in interpreting these trends, because the U.S. network comprised about 15 times as many sampling sites in 1977 as 1957. In addition, a great variety of site locations and sampler positions (height above ground, etc.), all meeting the EPA monitor siting criteria, exist in the network. Nevertheless, appropriate statistical treatment of the monitoring data confirms the above trends and the more recent levelling off in rate of annual mean TSP reduction at many sites.

No trend data are available for inhalable particulate matter (normally $\leq$ 15 μm in diameter by the current EPA definition) or respirable particulate matter (similarly, $\leq$ 2.5 μm in diameter), since the U.S. inhalable particulate network is just getting underway (17).

2.2.3 Canadian National Trends

Canadian experience has been similar to the U.S. experience described above.

The National Air Pollution Surveillance (NAPS) network was established in January 1970. The monitoring methods employed for particulate matter are the

HiVol method for suspended particulates (equivalent to the term total suspended particulate matter, TSP, used in this report) and the soiling index (or coefficient of haze) tape sampler. As of the end of 1977, there were about 100 of each type of instrument in operation in the 53 cities that comprised the NAPS network.

Between 1970 and 1979, (39,42-44) the network average of annual geometric means for both suspended particulate matter and soiling index generally decreased. The year-to-year rate of decrease for both quantities was small during the latter part of this period.

A significant percentage of the NAPS stations reported exceedences of both the maximum acceptable suspended particulate matter level of 70 μg/m^3 (see Section 3.2.1) and the maximum desirable level of 60 μg/m^3 during the period 1970-79. As of 1978, 50% of the stations were still reporting annual geometric mean suspended particulate matter concentrations in excess of 60 μg/m^3 (42,43). Similarly, 82% of the stations reported 24-hour maximum concentrations in excess of the maximum acceptable level of 120 μg/m^3. A notable statistic is the percentage of stations reporting a 24-hour maximum suspended particulate level in excess of the maximum tolerable concentration of 400 μg/m^3. This proportion remained relatively constant at about 7 percent between 1974 and 1979 (39,42-44).

In summary, national trends in suspended particulate matter levels show improvements over the past ten years. Certain statistics, however, indicate that many stations are experiencing problems in meeting annual average objectives and that most stations are having difficulty in meeting the short-term (24-hour) objectives, this being so despite concerted efforts on the parts of regulators and industries to reduce emissions.

NAPS data are reported monthly and summarized in annual reports by Environment Canada's Air Pollution Control Directorate (39,44).

2.2.4 Ontario Trends

A report issued in January 1978 (45) summarized monitoring data from the Ontario Air Quality Monitoring Network for the period 1971-76. Trends analogous to those summarized in the preceding section are evident in the Ontario data.

The first systematic monitoring of air pollutants by public agencies in Ontario began in the early 1960s in the Toronto area. In 1967, monitoring stations in Toronto and in other areas of the province were amalgamated under the Government of Ontario.

Between 1971 and 1976, both total suspended particulate matter (TSP, equivalent to the Canadian federal NAPS designation, suspended particulates) and soiling index (coefficient of haze, COH) levels measured in the Ontario network declined significantly. TSP is measured at about 150 sites equipped with HiVol samplers and COH at about one-half that number of sites by means of modified Hemeon/AISI tape samplers.

TSP levels averaged over the network decreased generally by about 33% between 1971 and 1976. This statement is also true for a selected group of stations, comprising those that had been in operation throughout the six-year period. Change during the latter three years of the period was more gradual than between 1971 and 1974. The trend during this latter part of the period was judged to indicate change "...characteristic of the approach to a steady level" (45). This judgement was based on the median value of the annual geometric mean and of other characteristic statistics of the network average TSP, such as first and ninth deciles and first and third quartiles.

Paralleling the national trends in Canada and the U.S. for the 1970's, the percentage of stations meeting the Ontario annual criterion (60 $\mu g/m^3$) increased from about 10% in 1971 to over 50% in 1976. Expressed in another way, despite numerous abatement programs undertaken in this period, many stations were still reporting TSP exceedences during the late 1970's. Likewise, the percentage of stations exceeding the Ontario 24-hour criterion (120 $\mu g/m^3$) on one or more occasions changed very little between 1972 and 1976, fluctuating around 90%.

The trend with time of the soiling index during the 1970's was not as marked as that for TSP. In fact, the median value of the soiling index decreased by only about 4% between 1971 and 1976. Virtually all stations in the Ontario network at which soiling index is measured met the annual criterion (0.5 COH), but about 50% did not meet the 24-hour criterion (1.0 COH) during the 1970's.

The different characteristics of the trends for TSP and soiling index may possibly be explained by the fact that the COH tape sampler measures particle concentration by a different principle (see Section 2.1.1).

2.2.5 Trends for Hamilton

Air quality data from Ontario Ministry of the Environment (MOE) and NAPS stations in Hamilton are summarized in the proposal which led to this study (46) and in several recent MOE reports (47-49). MOE data indicate that measured and estimated point source emissions in the Hamilton airshed dropped from 56 x 10^6 lbs/year in 1970 to 16 x 10^6 lbs/year in 1979 (a 71% reduction); whereas TSP levels decreased from an airshed average annual geometric mean of 131 $\mu g/m^3$ in 1970 to an average of 79 $\mu g/m^3$ over the period 1976-79 (a 40% reduction). The rate of decrease appeared to level off between 1976 and 1979.

Soiling index (COH) decreased generally during the 1970-79 period, but more gradually than TSP. This behavior is similar to that described above with respect to province-wide trends in soiling index during this period.

Dustfall measurements in Hamilton did not show a discernable trend. Recall that this measurement is a qualitative indicator of atmospheric loading of large, settleable particles. Mean dustfall values for MOE stations in the Hamilton area fluctated around (9.8 $\pm$ 0.6) $g/m^2/mo$ from 1970 to 1979.

Hamilton's Air Pollution Index (API) did not exceed the alert level of 50 between October 8, 1970, when the API reached 56 and December 21-22, 1979, when it reached 55. The advisory level of 32 has been exceeded several times each year between 1970 and 1979 (47-49), ranging from twice in 1970 and 1973 to 23 times in 1971. From 1974 to 1978, the number of exceedences of the alert level fluctuated around 9 $\pm$ 2 times per year with no discernible trend during this period. More recently, the advisory level was reached 22 times in 1979. Since the API is a 24-hour moving average of a function that combines COH and SO_2 concentration (see Section 3.1), the observed exceedences are consistent with experience elsewhere regarding short term average atmospheric loadings. That is, although annual average levels of TSP, etc. have generally decreased toward ambient air quality standards or objectives in North America, the frequency of short term exceedences has changed less dramatically during the past ten years.

2.2.6 The Role of Meteorological Conditions in Air Quality Trends

At this point, a word of caution should be interjected. None of the above trend analysis has taken into account the potential effects of meso or microscale variations in average annual atmospheric ventilation factors.

Significant changes in the average seasonal or annual movement of air through an urban airshed can occur from year to year. Such changes may exhibit trends on an extended scale of time that produces a trend, apparently resulting from air quality management activities, when in fact, natural factors are responsible.

Since this concept is very often overlooked, it is appropriate to define it in somewhat more detail. To put it simply, the concentration of an air pollutant depends not only upon its emission rate (kg/h, say) into an airshed, but also upon the rate at which a volume of clean air is advected into the airshed (km^3/h, say) to dilute the emission. This latter quantity can be thought of as a ventilation factor. It depends upon the windspeed crossing an airshed of given area and upon the atmospheric mixing height. The mixing height is determined in part by the intensity of solar radiation. A discussion of this point can be found in reference (49) on Hamilton air quality.

The history or trajectory of the advected air parcel may also affect the pollution potential of a given quantity of emission over a period of time. For example, a season dominated by the passage of relatively clean Arctic air might experience better apparent air quality than the same season in a different year that is dominated by air parcel trajectories over other urban or industrialized areas.

Any or all of these factors may have systematic or cyclical trends superimposed on their normal diurnal, daily, seasonal or yearly patterns. Such trends may be described generally as trends in airshed ventilation.

Kneip has shown for New York City (50), for example, that normalization of air quality data by approximate airshed ventilation factors removed many apparent year-to-year trends for TSP during the 1960's and 1970's. That is, the apparent trend may not have been the result of air quality management abatement programs but instead the result of more or cleaner dilution air being provided by natural atmospheric processes acting over this period of time.

An extended discussion of this subject is inappropriate here. The point is that meteorological variables affect air quality not only on a diurnal and day to day basis, as is commonly understood, but may also effect air quality in the longer term. Hamilton, because of its geographic location, topographic features, and the presence of a large urban and industrial heat island affect can be subjected to strong inversion conditions quite frequently.

2.2.7 Rationalization of Observed Trends in Air Quality Regarding Particulate Matter

Keeping in mind the previous paragraphs, it still seems proper to conclude that there are anomalous differences between trends (whether real or apparent) for various indicators of airborne particulate matter, air quality and inventoried emissions from industrial and other regulated sources. It is clear that one has to look to other types of sources in order to explain the observations summarized above. The following section attempts to identify the reasons for the anomalous air quality trends for particulate matter and the types of sources that must be considered.

2.3 Traditional and Non-traditional Sources

Section 2.2 described a number of trends in air quality with respect to airborne particulate matter that could not be explained in terms of traditional air quality management goals and strategies. That is, although the past concentration of regulatory agencies and industries on reducing particulate emissions from major industrial point sources had produced significant reductions in ambient suspended particulate matter levels, these levels were not decreasing in proportion to emissions. In most urban areas, air quality standards and regulations were bein approached but not met. It was becoming clear during the 1970's that continued emphasis on controlling stationary point sources would not bring about the attainme of the air quality objectives, especially the shorter-term ones. Thus, it was evident that control of emissions from non-traditional sources would be necessary in order to achieve these objectives.

For the purposes of further discussion, operational definitions of "traditional" and "non-traditional" sources will be useful. Air pollution regulatio have been aimed at traditional industrial stack emissions and process fugitive emissions. These traditional categories include such sources as fuel combustion and process sources that are exhausted through well-defined stacks or vents, and vehicle tailpipe gaseous emissions. Traditional industrial fugitive sources that also have been regulated to some extent are open process sources that are not fitte with stacks or vents, and storage bins or piles for process materials, solid fuels and solid wastes.

Non-traditional sources of suspended particles, that is, those that have not been addressed extensively in the past, include such sources as resuspended street dust, fugitive dust from construction and demolition operations, vehicle exhaust particulate emissions, wind/or vehicle-generated dust from unpaved roads and parking lots, and other general sources generated by human activity, especially in urban areas.

Excellent reviews of this subject have been given in a major report on urban suspended particulate matter non-attainment problems in the U.S. (40), in several papers by Pace (51,52), and in the proceedings of two recent symposia on measurement and control of fugitive emissions sponsored by the U.S. EPA (52, 53).

The effects on air quality of these non-traditional sources of particle emissions need to be understood in order to develop rational control strategies. It has been estimated for the U.S. that sources in the non-traditional category contribute 25 to 35 $\mu g/m^3$ to typical urban suspended particle levels, or as much as 40 to 70% of observed levels (40).

By the mid-1970's, there had been identified a need to develop methods to quantify these emissions before sound control strategies could be devised. This need has been only partially fulfilled.

The development of the means to quantify non-traditional sources is reflected in the various editions of the U.S. EPA's standard reference on air pollution emission factors: Publication AP-42 (54). The early editions of this work contained no data on fugitive emission sources. A supplementary chapter on fugitive dust sources did not appear until December 1975.

The next step in the development of quantifying the contribution of non-traditional fugitive dust sources to suspended particulate matter levels was the microinventory concept. The microinventory approach is described in an EPA report by Pace (51). The 16 volume EPA report on the "National Assessment of the Urban Particulate Problem" (40) provides data from 14 U.S. cities which led to the development of the microinventory technique. The application of this technique to data generated during the Hamilton study is described in detail in Sections 3.4 and 5. It will be introduced briefly here.

By considering various point and fugitive dust sources that could contribute to particulate loading at a sampling site, Pace was able to show that suspended particulate matter loadings measured at several sites in four cities could be correlated (by regression analysis) with the properties of a small number of different source types. The critical step is the compilation of a list of all of the sources that may impinge significantly on a sampler. In the approach developed by Pace, this means identifying and locating every source of fugitive dust and other particle emissions within one mile of the sampler, all point sources within five miles and all vehicle traffic sources within 200 feet. Hence the name microinventory.

Emission factors are applied to each source and a multiple linear regression is carried out on these source terms ("AREA", "POINT" and "LOCAL") against the measured annual mean suspended particulate matter loadings. The result is an empirical equation that, in principle, can be used to predict annual mean TSP on the basis of the microinventory data for the area around any other sampler.

The importance of this approach to the development of an air pollution control strategy is the identification of the types of sources that make the greate contribution to TSP at a given location.

The microinventory, however, does not identify individual sources or source types within the microinventory categories. Spatial and temporal variations of TSP, combined with meteorological data, may be analyzed to infer quantitative contributions from some individual sources, especially point sources. In order to identify specific sources, it is usually necessary to determine the physical and chemical characteristics of source emissions and collected particulate samples.

Source and ambient particle characterization are important to quantify the relative contributions of sources and to assess the health and ecological effects of particles from specific sources or source types. The latter effects depend upon the composition and form of the particles.

Informed decisions about source emission control upon a detailed understanding of the characteristics of the aerosol that makes up its atmosphere. The following section reviews earlier studies conducted in other urban areas with the objective of characterizing atmospheric particulate matter.

2.4 Urban Particle Characterization Studies

Over the past decade, numerous studies to characterize the urban suspended particulate matter problem have been reported. Many of these were concerned only with specific topics such as evaluating existing air quality as affected by suspended particulate matter, establishing trends, or determining compliance with air quality standards. Some have attempted to apportion the TSP among the known sources.

It has been frequently assumed that traditional industrial sources were the primary contributions to observed loadings of airborne urban particles and that control of these sources would lead to attainment of desired air quality standards. However, experience has shown that at many locations, annual average air quality objectives for total suspended particulate matter are not being realized despite concerted efforts on the parts of regulators and industries to reduce emissions (see Section 2.2). It appears that control of emissions from other non-traditional sources is needed in order to achieve these objectives.

A rational control strategy based on the most cost effective options requires a good source apportionment of the observed receptor TSP. Several studies have attempted to characterize urban TSP not only with respect to its chemical and physical characteristics but also as to the source contribution. A selected number of these studies are briefly summarized below.

2.4.1 California Aerosol Characterization Experiment (ACHEX) (55)

This study was carried out in 1972 and 1973 at several urban and non-urban locations in the San Francisco Bay and the South Coast Basin, covering the Los Angeles area. The objective of this early study centered on the question of the sources and evolution of aerosols in urban air as they are superimposed on a natural background, particularly how they relate to visibility degradation. The observations cover a wide variety of parameters including physical and chemical properties of aerosols, pollutant gas concentrations, and meteorological variables.

Monitoring was carried out over several months during 1972 and 1973 using a few fixed stations supplemented by an elaborately instrumented mobile laboratory. Instrumentation included condensation nuclei counters, optical particle counters, electrical mobility analyzers, rotating drum impactors, integrating nephelometers, and HiVols. A range of gaseous pollutants and meteorological parameters were also monitored.

A comprehensive protocol of chemical analysis of aerosol samplers was carried out. This included determinations of carbon, major ions and metals. Neutron activation analysis (NAA), X-ray fulorescence (XRF), mass spectroscopy, photoelectron spectroscopy (ESCA) and wet chemical analysis methods were all used.

Sites were chosen to be located such that sampling would be:

(a) enriched significantly by a major source (or identifiable sources),

(b) representative of receptors of a mixture of pollutants and air masses with a potential for significant changes in air chemistry, or

(c) representative of non-urban sites.

Major Findings. Source apportionment of urban aerosols was inferred semi-quantitatively by a consideration of factors such as knowledge of source elemental compositions, analysis for trace elements from various source categories (e.g., automobile exhaust - Pb and Br, soil components - SI, Al, Na), observed background and source impacted site data, correlations between observed elements and meteorological factors and the dependence of elemental composition on particle size.

The aerosol background of soil dust, sea salt and moisture appeared to be a significant fraction of the urban aerosol in California accounting for about 20% or more of the total mass concentration. Those particles consisting of carbon, nitrogen or sulphur compounds were identified as secondary aerosols (i.e., those formed as a result of photochemical reactions and gas to particle conversions) and accounted for more than 50% of the total aerosol particle mass. Particles directly related to primary emissions from transportation sources were estimated to account for about 10% of the TSP while, in general, industrial emissions contributed only about 5% of the TSP.

2.4.2 Chicago Area Urban Aerosol (56)

In this report, the then new method of chemical element balance (57) was applied to data available from the Chicago area. Tracer elements from particle emission source types were used and fitted to observed receptor elemental concentrations. Source coefficients were determined defining the relative contribution of each source to the observed aerosol. This method used a relatively small number of tracer elements as compared to the later developed chemical mass balance procedures (see Section 2.6).

Chicago Aerosol Sources. Six general categories of airborne particle sources in the Chicago area were identified (58): automotive emissions, coal burning and coke production, fuel oil burning, iron and steel production, cement manufacturing and soil erosion. Typical elemental compositions for each of these components were selected as published by a number of sources (see reference 56 and other references therein). A matrix of 22 elements was used but only seven "tracer" elements were applied to the chemical element balance calculations.

Receptor Aerosol Compositions. Two approaches were used. In the first, a "model aerosol" was constructed. This was intended to represent a typical aerosol found in Chicago. The composition of the model aerosol was formulated based on data published in several studies carried out in Chicago from 1968 to 1971. Using the source categories listed and their tracer elements, chemical element balance calculations were performed on the model aerosol to determine source apportionment.

In the second approach, data on multi-element concentrations at 22 stations during one 24-hour period in 1968 (59) were used to calculate source apportionment at each site. The results determined variations across the city in the relative contributions of the various sources to the aerosol mass and in the burden of individual elements applicable on the study day.

Major Findings. A major weakness in this study is the use of Al as a tracer for both the soil related particle source and that associated with coal burning and coke manufacturing. The results depend on the proportion of Al contributed by each of these sources. The authors considered the assumption that coal and soil sources both contribute equally to the observed Al burden was the best estimate of actual conditions.

For the model aerosol, the sources used accounted for about 36% of the total particle burden. The soil component was the largest at 18%. Automotive emissions accounted for less than 3% and fuel oil combustion about 1.5%. The component attributable to steel manufacturing (including coke production) accounted for about 10% of the total particle burden. Sulphate and nitrate were found to account for about 17% of the model aerosol mass and when included in this source listing, about 53% of the aerosol mass was accounted for. Although data were not available, it was estimated that non-carbonate carbon could contribute as much as 40% of the total aerosol.

During the single day when aerosol samples were taken and characterized at 22 sites, the meteorological conditions were not ideal. Due to the passage of a warm front, winds were high and variable (135° change during the sample collectio period) and some precipitation occurred. This made interpretation of the data difficult in terms of the effect on air quality attributable to specific sources. Nevertheless, the results were generally similar to the model aerosol and the metho was demonstrated to be useful in obtaining real distributions of source contributions to both total aerosol mass and elemental burdens.

2.4.3 Washington, D.C., Aerosol Characterization (60)

This study represented a much improved application of the chemic mass balance (CMB) method. The main reason for this improvement was the use of more elements in the CMB fit of sources to receptors. The inclusion of Mn and As helped to distinguish between the similar coal and soil source components. Zinc was used as an indicator of refuse incineration. Further, the use of source elemental abundance data based on actual stack tests rather than analysis of feedstock or material collected from emission control equipment provided a better sourc element matrix. Washington has few industrial sources that would contribute material of unusual concentration patterns and so provides a good location to use and test CMB models.

The study was based on a series of samples taken at four sites in Washington in 1974. These 24-hour samples were collected on Nuclepore filters which were subsequently analyzed for total of twenty-seven elements using neutron activation analysis (NAA) and atomic absorption spectroscopy (AA). Ten of the samples analyzed were used in the chemical element balance. Samples were selected to include a broad range of meteorological conditions.

Source Category Elemental Matrix. Six major source categories were used: soil, marine, coal combustion, oil combustion, incineration and motor vehicle exhaust. Each source was characterized for 27 elements, of which eight were used in the chemical mass balance calculations. Since the standard deviation in elemental composition analysis varied for each of the eight elements used in the CMB, the least squares CMB fit was weighted accordingly. This procedure is approximately equivalent to minimizing the squares of the percent deviations.

Major Findings. The results of the CMB calculations indicate that the source categories used account for about 55% of the total TSP. Of these, the soil component is the largest at about 30%. Motor vehicle emissions account for 12% and coal combustion 8%. Oil combustion, sea salt, and incineration each contribute about equally to the TSP for a combined total of about 5%. Although no direct measurements were made, it was estimated that ammonium, nitrate and sulphate contribute about 22% to the TSP. These secondary aerosol particles would be expected to be brought into the city by long-range transport. It might reasonably be expected that a significant fraction of the balance of the TSP (23%) could be accounted for by non-carbonate carbon particles.

2.4.4 Charleston Aerosol Study (61)

This study was carried out during a 21-day period in summer 1976 at one urban site in Charleston. Five dichotomous samplers were used simultaneously for 24-hour periods. The samplers were equipped with either Fluoropore or quartz fiber filters. In addition to mass loadings, a wide range of elements and ions were analyzed for and the results interpreted using both correlation methods and factor analysis.

XRF was used to analyze for elements heavier than magnesium. Proton induced Gamma-Ray Analysis was used to obtain measurements of total carbon, nitrogen and sulphur. Combustion methods were used to measure non-carbonate carbon. Ion exchange chromatography (IC) was used to measure sulphate, nitrate and sodium while an ion selective electrode was used to measure ammonium.

The results were analyzed by correlation methods and factor analysis. The correlation analysis identifies pairs of parameters which are significantly correlated with each other. Highly correlated species may come from the same primary source or secondary transformation process, or the correlation may indicate the species are carried together in the same air mass. Factor analysis identifies relationships between groups of elements. The observed variance in the measured elements is represented by a number of factors made up of combinations of elements (see Section 2.6).

Major Findings. Measured elements were found to concentrate in one or other of the two size fractions obtained by the dichotomous samplers, with the exceptio of non-carbonate carbon which was found to be about equally distributed between the two. Fine particle nitrogen was almost total in the form of ammonium while fine particle sulphur was all in the form of sulphur. Ammonium and sulphate were stoichiometrically consistent with $(NH_4)_2SO_4$ for the fine fraction.

On average, about 65% of the total collected aerosol mass was identified with known or likely chemical compounds. About 26% was due to $(NH_4)_2SO_4$, the largest identified component which, presumably, comes into the city by long-range transport. Crustal type material (soil, coal ash) account for about 20%, and non-carbonate carbon 16% of the aerosol mass.

Factor analysis identified four factors which accounted for 83% of the variance in the data set. The sources were consistent with crustal material (likely from soil and/or coal ash), ammonium sulphate, automotive exhaust, and a fourth source of uncertain origin. Factor analysis does not allow derivation of the relative contribution of each source to the observed receptor aerosol mass. It is, however, useful as used here where no predefined source category element matrix is available.

2.4.5 Fourteen City Study (40)

This report was prepared in order to review the national TSP criteria situation in the United States. Fourteen American cities were selected for study to identify the major factors affecting TSP attainment. No special sampling was conducted: existing data, namely HiVol monitoring information, were used to determine the contributions of various sources of TSP.

Three hundred HiVol filters from the 14 cities were examined by optical microscopy. These filters were selected from the three months in 1974 in which highest TSP levels were recorded and from the three months in 1974 in which the lowest TSP levels were recorded. Fifteen HiVols received detailed physical examinations, eight were chemically analyzed and four were particle sized. The particles were categorized - minerals, combustion products (soot, flyash), biological materials (pollen), and miscellaneous (rubber). It was found that single results from microscopic analyses can be very misleading although composite results from several analyses are very useful and can provide reliable results.

Major Findings. The findings from these data indicated that there was a direct relationship between the daily TSP concentrations and average daily level of traffic (ADT) and an inverse relationship between TSP and the distance of the monitor from the traffic, measured by the slant distance -

$$SD = \sqrt{(\text{height})^2 + (\text{distance})^2}$$

A comparison of the ADT/SD to the TSP concentration implied that a linear relationship could be assumed to exist with good correlation. The relationship between ADT and slant distance has a significant impact on the interpretation of TSP levels measured by a HiVol anywhere near a street with significant traffic.

It was found that non-traditional fugitive emissions (see Section 3.3) could add up to 25 $\mu g/m^3$ to the observed TSP at some sites.

2.4.6 Denver Area Aerosol Study (62)

The results of this study are based on aerosols collected by an automated dichotomous sampler in Denver, Colorado during 1979. A virtual dichotomous sampler was used with teflon filters over a mix of 12-hour and 24-hour periods. Some samples were also taken using quartz fiber filters.

Samples were analyzed for mass by β-radiation attenuation and for elements by XRF. Major ions were determined by IC and non-carbonate carbon by combustion methods.

The data obtained were analyzed by chemical element balance. The aerosol was described in terms of six contributing source components; sulphate and related cations, motor vehicle exhaust, shale, limestone, salt, and refuse incineration.

It was assumed that all of the sulphate present was in the form of ammonium sulphate. Experiments showed that sulphate in fine particles occurs primarily as sulphuric acid or ammonium sulphate (63). During normal sample handling prior to analysis, all of the acid sulphate was assumed to have converted to ammonium sulphate.

Motor vehicle exhaust refers to primary tailpipe emissions and was identified by bromine and lead. A mix of cars and diesel powered trucks was assumed in order to derive expected emissions of bromine and lead.

A detailed multi-element analysis of crustal matter in the Denver area was not available but it was felt that their applicability would have been unclear in any case due to the variability of the possible sources of crustal material. The crustal component was divided into both shale (silicon rich) and limestone (calcium rich types). The salt component resulted from the observation of high chlorine concentrations in the winter months; presumably due to the application and resuspension of salt used on streets for snow control. The observed chlorine did not correlate well with other elements but the samples were not analyzed for sodium. The inclusion of refuse incineration is important since this component is a significant source of several elements, especially zinc, although its contribution to the total observed aerosol mass is not large.

The method developed by Watson (64) was employed in the CMB analysis of the data. Weighting factors were used in the least square fits which incorporated the uncertainties in elemental concentrations in both the receptor aerosol and the source particles.

Major Findings. The six components plus unexplained carbon and nitrate accounted for all of the particle mass collected. Seasonal variations showed that the road salt component was only important during the winter months when it contributed about 6% to the TSP (primarily in the coarse fraction).

About 80% of the motor vehicle exhaust component was found in the fine size fraction and, although the magnitude of this component was larger in the fall-winter season, its percentage contribution to the total mass (∿ 25%) was reasonably constant throughout the year. This was attributed to seasonality of the meteorological dispersion factors for Denver rather than a variability in source strength.

The refuse incineration component was found to be present in significant quantities in both size fractions. However, the total contribution to the observed aerosol mass was less than 1%. Both crustal components were primarily present in the coarse fraction. The shale type was by far the largest with an average contribution of 32% to the aerosol mass. Limestone contributed about 3% to the aerosol mass. Ammonium sulphate was primarily found in the fine size fraction. It was estimated to account for at least 10% of the aerosol mass.

Only about 20% of the total observed carbon was accounted for in the CMB calculations, even though carbon represented a significant portion of the total mass (about 25%). Other sources of non-carbonate carbon must be present but not included in the CMB source matrix. Possible candidates include oil, gas or wood combustion.

2.4.7 Philadelphia Particulate Matter Study (65)

In this study, urban particulate matter was sampled using conventional HiVols at trailer-top level, at three heights on a 12 meter tower near an intersection, and at rooftop level (11 m) on either side of the main street at distances from 15 to 60 meters. A dichotomous sampler was used to obtain size distribution information and to allow for chemical analysis for a few elements. A GCA ambient particle monitor was used to determine short-term (e.g. one-hour) changes in particle concentrations in two size ranges.

Major Findings. This study was primarily directed towards quantifying the contribution of vehicle generated airborne particles in urban areas and therefore the data were not analyzed using CMB or other statistical methods to identify and apportion other sources to the observed TSP.

The results confirmed that vehicle related particles (tail-pipe emissions, tire wear, reentrainment) impact severely on the TSP of Philadelphia. It was estimated that street-level contributions to annual average TSP levels measured at an adjacent trailer-top monitor were in excess of 40 $\mu g/m^3$. The contribution of vehicle related emissions to citywide particle concentrations as measured at roof-top levels was not well separated from background concentrations but was estimated to be about 20 $\mu g/m^3$.

A short test was carried out to determine the effect of intensive street flushing on TSP levels. Concentrations were found to be as much as 100 $\mu g/m^3$ higher than expected based on observations at other locations within the city. This phenomenon was explained by assuming that vigorous, forced flushing, plus splashing by motor vehicles, redistributed particulate matter that had previously become concentrated adjacent to the curbs, and that a large proportion of this redistributed particulate matter became airborne as soon as the street was dry. This hypothesis was supported by a strong relationship between traffic volume and TSP concentrations during this period.

The contribution of vehicular traffic to ambient TSP results from the tire wear, tail pipe emissions and, most importantly, reentrainment of road dust. In residential areas, this source was found to add from 12 to 20 μg/m^3 to the TSP. In commercial and industrial areas, this figure averaged from 25 to 35 μg/m^3 with individual sites as high as 50 μg/m^3.

Construction and demolition activity were found to have a significant local impact adding from 10 to 15 μg/m^3 within one half mile from the site, and up to 3 μg/m^3 as a city wide effect.

As expected, meteorology has a major effect on observed TSP. Precipitation in excess of 6 mm typically can reduce TSP values by up to 50% and a noticeable reduction persists into the second day. An annual increase in precipitation of 25 mm was found to decrease the annual geometric TSP mean by 0.4 μg/m^3. The effect of wind speed is very site specific although the highest TSP values occur with low wind speeds and poor ventilation. The average wind speed did not appear to affect TSP levels presumably due to competing influences of increased ventilation and dust reentrainment with increased wind speed. The number of degree heating days (as defined by the sum of the difference of daily mean temperatures from 18°C) was found to affect the TSP such that an increase of 1000 degree heating days in a year increases the annual average TSP by 2.5 μg/m^3.

The study also found that the long-range transport of particles of anthropogenic origin into urban areas contributes significantly to the TSP. This includes sulphates, nitrates, ammonium and organic compounds.

2.4.8 Boston Aerosol Study (66)

This study represents an analysis of data collected on aerosol composition in the Boston area. The technique used is a form of factor analysis called target transformation factor analysis (TTFA) (67). This method, unlike previous applications of factor analysis, allows for the incorporation of actual source element concentration profiles and a direct calculation of the contribution of each source to the receptor aerosol load. The calculation is similar to CMB methods although it is not necessary to identify and characterize all contributing source components prior to the analysis. Unlike CMB methods however, TTFA requires several samples at a given receptor site of variable loading for which it is assumed that the sources identified contribute in a fixed ratio.

Samples were collected over a five month period at eight sites in the general metropolitan Boston area. A total of 90 samples were obtained on which a useful total of 16 elements were determined using neutron activation analysis. A hierarchical cluster analysis determined that the data set fell into two distinct clusters. The first consisted of 57 samples coming primarily from sites located at the periphery of the city which were classified as suburban. The second contained 33 samples from sites nearer to the city center which were classified as urban. Each cluster was treated separately.

Major Findings. The factor analysis showed that most of the observed variation could be represented adequately using six source factors (68). For the TTFA, a set of ten possible source vectors were tested. These included soil, oil combustion, coal combustion, refuse combustion, motor vehicle emissions, marine salt, carbonates, shale, NBS flyash and road dust. The six test vectors which were found to result in the best overall agreement were soil, oil combustion, marine salt, motor vehicle emissions, refuse burning, and road dust.

The elemental composition of the soil component is similar to material resulting from the combustion of coal. In the Boston area however, the amount of coal combustion is small and was therefore not considered to have contributed to the soil component. The road dust component could include other unknown industrial activities. A further more definite identification would have required other elements to be analyzed. For example, calcium and magnesium were not analyzed for but are two of the primary indicators of cement. Arsenic tends to be enriched in coal flyash and so would also have been a valuable parameter for which to analyze.

Assuming chemical compounds in which the element measured were likely to be present, the mass contribution of each source category to the TSP was calculated. Since several key elements were not determined (e.g., carbon, sulphur, nitrogen), the percentages of the total receptor mass was not calculated at the urban sites. An average of about 50 $\mu g/m^3$ is accounted for by the identified source factors. Soil was the largest component at about 20 $\mu g/m^3$. Mass contributed to the receptor aerosol by residual oil combustion was surprisingly large at about 15 $\mu g/m^3$. Road dust contributed about 8 $\mu g/m^3$, motor vehicle emissions 4 $\mu g/m^3$, and marine salt 4 $\mu g/m^3$. Refuse burning contributed less than 2 $\mu g/m^3$.

2.4.9 Portland Aerosol Characterization Study (69)

This study represents one of the largest and most comprehensive attempts to characterize and apportion urban TSP. Unlike most previous studies, considerable resources were devoted to the development of a full characterization of emission sources in the study area by means of a source testing program. Receptor aerosol samples were taken at several sites within the Portland airshed over a long enough period of time so as to obtain a statistically representative set of samples covering the range of meteorological conditions experienced in the area. Data were analyzed primarily by the use of CMB methods.

Source Emission Elemental Characterization. An ambient program of source characterization was carried out by actual source tests within the Portland airshed. A total of 28 categories of source types were evaluated which covered more than 95% of the airshed emission inventory. Particle size was determined as well as over 27 chemica species. This inventory was used for the source elemental matrix in the CMB calculations.

Receptor Aerosol Characterization. Six sampling sites were selected; two background, one general urban, one commercial-industrial-residential mix, and one residential. At each site there were two HiVols and two low volume samplers. The standard HiVol was used to measure TSP and carbon while the other HiVol was fitted with an impactor to obtain size information on TSP and carbon. One of the low volum samplers was used for TSP and inorganic species determination while the other was fitted with a cyclone to obtain particle size information on TSP and inorganic species.

Sampling days were chosen on the basis of prevailing meteorological conditions such that the resulting set of samples corresponded to the same statistical distribution of various meteorological conditions as experienced on average in the Portland area.

Analytical Methods. In addition to mass loadings and size distributions, more than 27 chemical species were determined using a variety of analytical techniques. These included ion chromatography, XRF, NAA, and carbon volatilization and flame photometric methods.

Major Findings. The TSP levels varied from 30 μg/m^3 (background values) up to about 80 μg/m^3. The fine fraction component averaged about 30% of the TSP. About 75%

of the TSP was accounted for by the source categories used in the CMB calculations. Of the remaining 25% of the TSP mass, a combination of 5% was sulphate, 5% nitrate and 8% volatilizable carbon which were each in excess of that predicted by the CMB. This left only about 7% unidentified TSP mass. It was found that background TSP (i.e., particles carried into the area from outside) contributed about one half of the observed TSP.

Of the chemical species analyzed, organic carbon was the largest component averaging 12% of the TSP and 32% of the fine fraction (size less than 2.5 μm). Other elements present in significant amounts were silicon - 11%, sulphur - 4.1%, aluminum - 3.2%, iron - 3.5%, calcium - 2.3%, sodium - 2.1%, and lead - 1.8%.

The calculated source category contributions to the observed TSP were variable. In the downtown Portland area, the largest component was geological or crustal material (soil, road dust) at 39% of the TSP. Vegetative burning was the second largest at about 15%. Automotive emissions were significant at about 9%. Marine sources contributed about 4% while emissions from the combustion of residual fuel oil contributed only about 0.8%. Primary industrial emissions contributed a total of only about 5%. Excess sulphates, nitrates and organic carbon which were not predicted by the CMB were presumed to represent an upper limit of contributions due to secondary particle formation. These totalled about 17% of the observed TSP.

2.4.10 Allegheny County Aerosol Study (70,71)

This study examined historical TSP data in the Allegheny County over the period 1975-1977. A variety of standard statistical methods in air quality data analysis were used covering a group of 24 TSP monitoring stations. In addition, dispersion modelling calculations were used to help identify industrial point and fugitive emission contributions to receptor sites. No receptor modelling was carried out. Particle identification studies were performed using scanning electron microscopy methods coupled with energy dispersive X-ray analysis (SEM/EDAX).

The results of this study are of particular interest since Allegheny County includes Pittsburgh and a large concentration of primary steel production to the southeast of the city. The Pittsburgh area has a heavy traffic density and construction activity capable of reentraining large quantities of particles. Finally, Western Pennsylvania has a micrometeorological climatology which makes it difficult to relate sources and receptors through modelling and monitoring. These factors are all similar to the situation in Hamilton. Further, like Hamilton, there had been substantial reductions in industrial point and fugitive emissions over the period 1971 to 1976 which were not paralleled by a similar general reduction in observed TSP levels.

The quantitative limitations and applicability of some aspects of the dispersion modelling and the interpretation of the particle SEM/EDAX work is unclear, however, the general results should be valid at least on a semi-quantitative basis.

Major Findings. The major source categories were divided into traditional, non-traditional, and background (see Section 2.3). Background TSP levels (i.e. particles carried into the study area from outside) were found to contribute significantly to the observed TSP. For a typical urban site, background sources contributed for 35% up to 85% of the TSP depending on the time of year. Traditional sources were only found to contribute from about 5% to 20% of the TSP while industrial non-traditional sources contributed from 5% to 10%. Urban non-traditional sources were found to be significant during some periods of the year and contributions ranged from 5% to 35%.

The importance of background particle sources is clear in this area. An annual geometric mean of about 47 $\mu g/m^3$ from such sources was determined. This county is downwind of the heavily industrialized Ohio river valley which probably accounts for the high background levels observed. Traditional sources typically account for 5 to 25 $\mu g/m^3$ of the TSP observed and contribute less than 10% to the annual geometric mean TSP at most sites. Industrial non-traditional sources contribute similar amounts to the annual geometric mean TSP as do traditional sources on average. The average contribution of urban non-traditional sources of particles to the annual geometric mean TSP was found to be about 30%.

These are average figures and considerable variability was found between sites. However, the important conclusion is that background and non-traditional sources are major contributors to the TSP observed and that control of only traditional sources may not lead to the attainment of ambient air TSP standards.

2.4.11 Suspended Particulate Matter in Hamilton

Airborne particulate matter has been monitored in Hamilton by the Ontario Ministry of the Environment and its predecessors for more than a decade. Methods used include HiVols, dust fall jars, and COH monitors (see Section 2.1 and 2.2). Studies have been reported which review and interpret these data and which attempt to identify observed TSP to various known sources through statistical analysis and dispersion modelling (72-78). However, no sufficiently comprehensive studies have been reported which adequately characterize source and receptor particles in order to allow source apportionment of the observed TSP to be carried out.

The trends in TSP for the Hamilton area are discussed in Section 2.2. An Ontario Ministry of the Environment report (73) has estimated the proportion of annual geometric mean TSP contributed by background transport into the area, local industrial contributions, and other city sources. This separation of source contribution was inferred from a consideration of TSP dependence on wind speed, direction, and time periods such a diurnal, weekday vs weekend and seasonal. At the Barton and Sanford API site, it was estimated for 1970 and 1977 that the background contribution to the observed TSP was about 35 $\mu g/m^3$, and that city non-industry sources contributed about 40 $\mu g/m^3$. Industry contributions were estimated at 60 $\mu g/m^3$ in 1970 and 22 $\mu g/m^3$ in 1977. This decrease parallels a similar percentage drop in industrial emissions over this time period. By 1985, further control of industrial emissions is forecast to reduce the TSP contribution from this source to 14 $\mu g/m^3$.

Thus in 1979, industrial sources were estimated to account for about 45% of the TSP. By 1977, this was reduced to 23%. If other city particle sources remain at a TSP contribution of 40 $\mu g/m^3$ until 1985, then, at that time, industrial sources are predicted to contribute only about 16% to the TSP while other city sources and the background source will contribute 45% and 39%, respectively. This implies that, with only industrial emissions being controlled, by 1985 city non-industry sources will contribute almost three times as much as industrial emissions to the observed TSP. Clearly these other city sources need to be considered in any effective control strategy.

2.4.12 Summary

The preceding sections demonstrate the variety of methods which have been used to characterize and source apportion urban particulate matter in several cities. These studies range from fairly simple considerations of TSP patterns to complex data sets and statistical interpretation approaches. Despite the diversity of cities and study methods used, the general major findings are found to be similar.

Characterization of urban airborne particles typically includes one or more of the following types of information:

- TSP
- size distributions
- concentration determination of chemical species (ranging up to 30 or more in comprehensive studies)
- morphological examination

Analytical methods used are such as:

- mass measurements by β-radiation attenuation or gravimetric means
- X-ray fluorescence
- ion chromatography and ion selective electrodes
- carbon analysis by combustion or volatilization and flame ionization detection
- atomic absorption
- mass spectrometry
- photo-electron spectroscopy
- microscopic analysis

Other parameters which have been considered in urban airborne particle studies are:

(a) Meteorological conditions such as wind speed and direction, atmospheric stability, precipitation, ventilation factors, and general climatology.

(b) Temporal variations such as diurnal, weekday vs weekend, and seasonal.

(c) Spatial relationships between sources and receptors.

(d) Topographic features.

Methods used to interpret gathered data bases are:

(a) Standard air quality analysis methods such as frequency distributions, log-normal plots, wind and pollution roses, correlations between TSP and other parameters, spatial and temporal patterns.

(b) Tracer studies in which unique markers are used which identify given sources of concern.

(c) Statistical analysis such as correlations between pairs of elements to establish common sources, and factor analysis to establish groups of elements which may be factored together to explain the observed variance in element concentrations.

(d) Receptor models such as chemical mass balance and target transformation factor analysis which link and apportion observed receptor element profiles with sources.

(d) Dispersion and transport models which link sources to receptors using emission data, and meteorological and topographical conditions.

Major Findings From Urban Particle Studies. The studies reviewed here show that in urban areas background particles (i.e., particles carried into the area from outside) contribute from 30% to 80% of the observed TSP with a typical contribution of 50%. The large percentage of this background material is composed of sulphates, nitrates and ammonium compounds in the small size fractions.

Industrial traditional source contributions to TSP range from 5% to 25%. In urban areas with nearby iron and steel production facilities, these industries contribute from 10% to 25% of the observed TSP. This figure includes particles from coal combustion and coke production. Non-traditional particle emission sources are estimated to contribute up to about 40% of the observed TSP. In addition to specific industries, typical source components usually included are vehicular related emissions, coal combustion, oil combustion, soil reentraiment, vegetation burning, refuse burning, road dust and marine sources.

Vehicular emission contributions to TSP are estimated to be from 10% to 25%, with the exception of Chicago and Boston where this figure appears to be less than 5%. Coal combustion TSP contributions have been usually included with industrial activity (e.g. iron and steel production) or included with the soil component. However, in Washington, D.C. this source component was estimated to contribute 8% to the TSP.

Residual fuel oil combustion generally was found to contribute from 1% to 2% to the TSP, except in Boston where this figure was a surprisingly high 15%. In Portland, where vegetation burning is important, this source was found to add 15% to the observed TSP.

The soil component was frequently found to be the highest single component ranging from 20% to 40% of the TSP. Road dust itself has been separated only in Boston, where it was found to contribute about 8% of the TSP. Refuse burning only contributes about 1% to 2% of the TSP but includes a variety of toxic metals not found in other sources.

Marine sources in coastal cities and salt during winter months for other cities has been found to contribute about 5% to the TSP.

In the Hamilton area, there were no data prior to this study to permit a proper source apportionment to be carried out. However, it is reasonable to assume that source contributions to TSP are not unlike those found for Chicago or Pittsburgh. Ontario Ministry of the Environment estimates for TSP in 1977 of 35% background, 25% industry, and 40% other city sources seems reasonable and consistent with findings elsewhere.

2.5 Urban Air Pollution Models

The air quality of a city in terms of total suspended particulate matter (TSP) is the net result of the source emissions distribution in the city, of the meteorological conditions which control the transport and dispersal of the pollutant, and of the interactions which remove particulate matter from the atmosphere.

In view of the complex interrelationships which can exist between the levels of emissions and the resulting air quality, an objective methodology is required for the assessment of relative contributions and generation of control strategies. Such a methodology is provided by Urban Air Quality Simulation Models (AQSM).

The utility of AQSM's results from two characteristics of simulation models:

(a) the model extends the spatial coverage of the monitoring network which must of necessity be limited

(b) by providing a simulated cause-effect link, the model allows the testing of alternative control strategies.

Because of the complexity of the processes which generate the observed TSP levels within the urban complex, such an evaluation poses a major challenge to the modeler's ability at simulating the physical processes realistically.

The objective of the following sections is to summarize the more significant models and methods developed to date and to present the basis for selection of the modelling approach which has been used to characterize loadings in the present study.

2.5.1 Atmospheric Diffusion

Most atmospheric pollutants are introduced into the lowest layer of air near the ground, and are transported and dispersed within a shallow layer extending to about 1 km above the surface. The description of the flow in this layer, the planetary boundary layer (PBL), has received a great deal of attention from atmospheric physicists over several decades, and significant progress has been made in understanding its nature.

The boundary layer is characterized by its turbulent nature, caused by the action of surface friction and sensible heat input at the ground-air interface. The principal area of investigation has been into the mechanism of transfer of heat and mementum within the layer and the resulting distribution of these properties and related properties of temperature, wind speed, wind direction, shearing stress, heat flux, r.m.s. turbulent velocity and scales of turbulence.

The dispersal of material released into the boundary layer, assuming that it has no effect on the motions within the layer, is similarly governed by the turbulent properties of the layer. A further assumption which is generally made is that particles of size less than approximately 20 to 50 μm behave essentially as an inert gas with respect to the dispersion process. This assumption should be a good approximation for the first hour of transport from the source.

There are currently three working hypotheses for dispersion, viz:

(a) statistical theory

(b) similarity theory

(c) gradient-transfer (K) theory.

A detailed comparison between the theories can be found in Pasquill (79), and a summary has been prepared by the same author (80).

In the statistical theory as originally proposed by G.I. Taylor, the spread of material from a point is described on a statistical basis in terms of the r.m.s. velocity and the Lagrangian auto-correlation function as

$$\overline{x_i^2}\ (T) = 2\ \overline{u_i^2} \int_o^T \int_o^\tau R(\xi)\ d\xi\ d\tau \qquad (2.5.1)$$

where $\overline{x_i^2}$ is the mean square particle displacement relative to a fixed axis along direction i

$\overline{u_i^2}$ is the mean square of the x_i directed wind speed fluctuations

$R(\xi)$ is the single-point Lagrangian auto-correlation coefficient

ξ $= T_2 - T_1$ is the time interval between successive velocity evaluations.

For this formulation to be valid, the turbulence field must be homogenous and stationary.

The auto-correlation function can be shown to satisfy

$$R(o) = 1$$

and

$$\int_o^\infty R(\xi)\ d\xi = t_L \qquad (2.5.2)$$

where t_L is the Lagrangin time scale and is bounded so that for small T

$$\overline{x_i^2}\ \alpha\ T^2$$

and for large T

$$\overline{x_i^2}\ \alpha\ T$$

These properties allow for a great simplification in the description of dispersion by statistical theory.

The similarity approach to turbulent dispersion was suggested by Monin (81) and later developed by Batchelor (82). In this theory, the basic approach is to relate the vertical turbulence (and hence spread of material) to the local friction velocity, or alternatively the scale of turbulence (or length scale). This approach can be strictly valid only in the constant stress layer (up to about 30 m above the surface) and thus has limited applicability to the more general problems of dispersion in the boundary layer.

The gradient transfer theory arises from an attempt to describe the dispersal of material by means of the fundamental mass-balance equation, which in terms of concentration of material can be written in tensor notation as

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x_i}(u_i C) = D_m \frac{\partial^2 C}{\partial x_i \, \partial x_i} + R\,(C) + S(x,t) \qquad (2.5.3)$$

where D_m is the molecular diffusivity

R is a source term dependent on C

S is an external source term

C is the concentration field and the Einstein summation convention is used for repeated indices.

If we write

$$C = \overline{C} + C^1$$

and

$$u_i = \overline{u_i} + u_i^{\,1}$$

where the primed quantities are turbulent fluctuations and the barred quantities are ensemble averages, then the averaged equation reads

$$\frac{\partial \overline{C}}{\partial t} + \frac{\partial}{\partial x_i}(\overline{u_i}\,\overline{C}) + \frac{\partial}{\partial x_i}\overline{(u_i^{\,1} C^1)}$$

$$= D_m \frac{\partial^2 \overline{C}}{\partial x_i \partial x_i} + \overline{R}(\overline{C} + C^1) + \overline{S}(x,t) \qquad (2.5.4)$$

In this equation, $\overline{u_i^{\,1} C^1}$ is a new independent variable representing the turbulent mass flux. In order to 'close' the equation, this variable must be related to the original variables. The gradient-transfer approach is to set

$$\overline{u_i{}^1C^1} = -K_i \frac{\partial \overline{C}}{\partial x_i} \qquad (2.5.5)$$

(no summation is implied)

It is also common to make the further assumptions that

- molecular diffusion (Dm) is negligible compared to turbulent diffusion.
- the atmosphere is incompressible ($\partial \overline{u_i} / \partial x_i = 0$)
- the reaction rate is not influenced by concentration fluctuations ($\overline{R(C)} = R(\overline{C})$)

Then the above equation takes on the form

$$\frac{\partial \overline{c}}{\partial t} + \overline{u_i}\,\frac{\partial \overline{c}}{\partial x_i} = \frac{\partial}{\partial x_i}\left(K_i \frac{\partial \overline{C}}{\partial x_i}\right) + R(\overline{C}) + \overline{S}(x,t) \qquad (2.5.6)$$

It has been shown by Seinfeld (83) that several conditions are required for the application of the above equation to the description of atmospheric disperison

(a) Temporal variations of S and R are gradual

(b) Spatial variations of S are gradual

(c) The time scale of chemical reactions as described by R is much larger than the Lagrangian time scale of turbulence.

(d) The time and space scales of the material cloud are much larger than the corresponding scales of turbulence.

These conditions are very rarely, if ever, realized in nature, and it has been concluded by some researchers (Corrsin (84)), that "the partial success of gradient transport models in turbulence is largely fortuitous, and certainly surprising".

The eddy diffusivities, K_i are functions of the space and time variables as are the velocities $\overline{u_i}$, so that a specification of these is required in the solution of the equation. The specification of the eddy diffusivities is highly problematic, in general, but some theoretical forms have been suggested for the vertical transfer term, namely

- momentum transfer form, using similarity hypothesis

- turbulence statistics form, arising from the Taylor theory (see Pasquill (80)).

Additional difficulties are encountered in extending the theory to stratified boundary layers.

The specification of the wind field in the diffusion equation for urban or regional scales must account for surface temperature variations and topographic features, as well as the turbulence features of winds in the boundary layer.

2.5.2 Urban Mesometeorology

It is apparent on physical grounds and from the discussion of the previous section that the wind and turbulence fields determine the dispersal of material in the atmosphere. The prediction of these fields in an urban setting which introduces discontinuities into the temperature and roughness parameters becomes a complex problem requiring computational resources beyond what is currently available. Consequently, simplifying assumptions are introduced to make the problem tractable, or alternative methods of specification are devised.

Wind - Fields. The simplest approach to generating mesoscale wind fields is to use measured winds over a network of wind observing stations and extend the data to a regular grid network by an interpolation technique. Wendell (85) developed an inverse square weighting procedure in which the individual velocity components at a given grid square are determined from all observed winds by weighting each observation with the inverse square of the separation distance between the grid square and the observation point.

This method can introduce wind field divergence in complicated flow situations. To circumvent the problem, various methods have been suggested to minimize the divergence problem. Dickerson (86) used the variational method to generate a non-divergent mass consistent wind field. Sherman (87) developed a mass consistent wind field program for the ADPIC model.

Modified potential flow models have also been suggested. Anderson (88) developed a model to modify the synoptic wind for topographic influences by means of the potential equation

$$\overline{\nabla^2 \phi} = \underline{u} . \underline{\nabla} h/H \qquad (2.5.7)$$

where $\underline{u}$ is the synoptic wind

h is the surface elevation

$\underline{\nabla}$ is the horizontal gradient operator and the bar indicates a mean over height H-h.

Scholtz and Brouckaert (89) have extended this approach by including a potential term for surface temperature anomaly, as well as katabatic effects.

Derrickson (90) has proposed a three dimensional numerical potential flow model incorporating arbitrary bourndary conditions and capped by an undisturb synoptic flow condition.

Wind and Turbulence Structure. Significant developments have also been made in the modelling of the plantetary boundary layer, the objective of which is to predict the development of the boundary layer parameters such as height, wind, temperature and turbulence structure.

In the initial stages, simplifications were used to make the problem tractable. Lavoie (91) and later Keyser and Anthes (92) advocated the vertical integration of the governing equations within the depth of the PBL and to allow horizontally variable fields. A two-dimensional numerical model for the urban hea island over Columbus, Ohio was presented by McElroy (93).

Bornstein (94) presented a two-dimensional (vertical) non-steady urban boundary layer model (URBMET) for simulating flow over a warm rough city which compared favourably with some observations of Oke and East (95) in Montreal.

Sheih and Moroz (96) developed a two-dimensional model for the lake breeze, while Barnum and Rao (97) used a two-dimensional model to predict the variation of mixing height in an urban environment.

Three dimensional models have been developed by Pielke (98), Pandolfo and Jacobs (99), Wyngaard et al (100) and Vukovich et al (101). The Boundary Layer Research Division of the Atmospheric Environment Service is carrying out research into numerical PBL model extending the method introduced by Pielke. For a review of this work, Walmsley and Reid (102) and Walmsley (103) should be consulted.

2.5.3 Modelling Approaches to Dispersion

The objective of atmospheric dispersion models is to simulate the time and space distribution of material released into the atmosphere. The most elementary problem arises in the simulation of a point source; this also being the building block in a number of urban scale dispersion models.

Analytical Solutions. The basic determinative equation for dispersion is generally taken to be given by Equation 6 of the previous section. The general equation does not allow an analytical solution, so that simplifying assumptions are necessary. The utility of the resulting analytical solutions then depends on the appropriateness of the assumptions to the problem being simulated.

If the eddy diffusivities are taken to be constant in space and time and the wind is assumed constant and uniform, no removal mechanisms are operative, and the atmosphere is unbounded, then for a instantaneous point release at the origin the concentration of material is given by

$$C(x,y,z,t) = \frac{S}{8(\pi t)^{3/2}(K_x K_y K_z)^{1/2}} \exp\left\{ - \frac{1}{4_t} \left\{ \left(\frac{x-\bar{u}t}{K_x}\right)^2 + \left(\frac{y}{K_y}\right)^2 + \left(\frac{z}{K_z}\right)^2 \right\} \right\} \qquad (2.5.8)$$

where it has been assumed that the uniform wind is directed along the x-axis.

For a continuous point source, the steady state solution is given by (the so-called Gaussian form)

$$C(x,y,z) = \frac{Q}{\pi\sigma_y\sigma_u} \exp \{- y^2/_{2\sigma_y}2 - z^2/_{2\sigma_z}2\} \qquad (2.5.9)$$

where Q is emission rate (MT^{-1})

$$\sigma_y = (2K_y t)^{1/2}$$

$$\sigma_z = (2K_z t)^{1/2}$$

and x-directed diffusion is ignored by comparison with advection of material with the mean wind.

The corresponding solution for an elevated continuous point source is

$$C(x,y,z,h) = \frac{Q}{2\pi\sigma_y\sigma z_u} \exp(-y^2/_{2\sigma_y}2) \ \{\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\} \qquad (2.5.10)$$

where a reflection term at the surface has been added (Gifford (1960)).

It is evident from the derivation that the above solution, assuming constant wind speed and diffusivity, are idealizations which are never met in actual situations. A number of more general solutions have therefore been developed postualting single analytic forms for the vertical profiles of u and K_z. These include the studies of Smith (104), Peters and Klinzing (105), Dilley and Yen (106), Heines and Peters (107), and Lebedeff and Hameed (108).

It has been pointed out by Pasquill (80) that, if power law profiles are postulated for u and K_z, then a Gaussian form for the vertical distribution is obtained if the exponents for u and K_z are idential. In addition to the above steady-state solutions, time dependent solutions in special situations have been derived, including the models of Quesada (109), and Saffman (110).

Due to the nature of the dispersion process, very little data exists for evaulating the various solutions. Much of the field data that has been gathere on diffusion is characterized in the form of plume spread σ_y and σ_z for a number of discrete turbulence regimes. These include the studies of Pasquill (111), the Brookhaven data (Singer and Smith (112)), and the TVA data (Carpenter et al (113)). In these studies, wind profile and turbulence variation are averaged out, so that the various forms of analyticl solutions cannot be directly tested.

Some pertinent data were also obtained in the field studies Project Prairie Grass and Green Glow Diffusion Program (Barad 114,115). Based on this data, Huang and Drake (116) claim good agreement for a non-Gaussian solution to the diffusion equations, based on power law forms for u and K_z and K_y (see also Yeh and Huang (117)).

Studies of dispersion in the urban environment indicate a pronounced difference in dispersion processes as compared to the rural environments, the diffusion being enhanced in the urban Boundary Layer (McElroy and Pooler (118), Clarke et al, (119)).

A physical modelling approach to diffusion evaluation has produced useful results for the modelling of dispersion in the mixing layer (Willis and Deardorff (120), Deardorff and Willis (121)).

Numerical Solutions. Due to the restricted applicability of analytical solutions, a great deal of effort has gone into studies which attempt to generate solutions to the dispersion equation under more general conditions using numerical techniques on a high-speed computer.

Two general approaches to the solution of Eq'n. 6 can be classified as Eulerian and Lagrangian. In an Eulerian approach, the diffusion equation is solved in a fixed co-ordinate system. The volume of interest is divided into a set of grid cells of fixed dimensions. Material is then advected and diffused from one cell to another according to a finite difference form of the equation.

Due to space and speed limitations of current computers, the grid size and time-step are limited; this causes spurious "diffusion" resulting from the advection term in the equation. Several methods have been developed to deal with this error, the most common in use being the moment method of Egan and Mahoney (122).

In the Lagrangian approach, the cell within which the pollutant is distributed is advected with the velocity field, and the material balance equation is taken to describe the transfer of material. In this approach it is generally necessary to smooth the wind fields and neglect horizontal diffusion (Johnson et al (123)).

Another method of avoiding the pseudo-diffusion problem was developed by Sklarew. In this "particle-in-cell-method", the advection and diffusion terms in the equation are combined by defining a diffusion velocity

$$U_d = - \frac{K}{C} \cdot \frac{\partial C}{\partial K} \qquad (2.5.11)$$

which is added to the field value of the wind. The total pollutant mass is simulated by a number of discrete particles which are transported with the modified velocity. Concentrations are defined in an Eulerian fixed grid network by count of the number of particles in each fixed cell at a given time (Sklarew et al (124)).

The dependence of dispersion on the form of the eddy diffusivity parameter has been evaluated numerically in a number of studies. Ito (125) solved the case of logarithmic velocity profiles for comparison with the Project Green Glow diffusion trials. Ragland and Dennis (126) have reported a model which deals with arbitrary diffusivity and wind profiles, and discuss the effects of changing the roughness conditions on dispersion.

Runca and Sardei (127) derived a two-dimensional finite difference model for a time dependent point source with arbitrary wind and diffusivity profiles. Numerical solutions for line sources have been reported by Denard et al (128), and for distributed area sources by Ragland (129) and Lebedeff and Hameed (130).

2.5.4 Urban Model Components

The term Urban Model is used to denote a system for making evaluations and predictions of the pollutant concentration fields within the urban environment.

The general model consists of four distinct components (Moses, (131));

- source inventory
- monitoring network for pollutants
- meteorological network
- mathematical dispersion model

The detail required in the source inventory and monitoring network is determined to a great extent by the type of mathematical model to be used. Some model require specification of the detailed wind and turbulence fields on a dense grid network of points on an hourly basis, and determine the concentration fields at a network of receptor points in a time sequence. Other models use a mean wind for the entire urban region to predict the concentration distribution at a given time in the static sense. Clearly, the meteorological input requirements for the two types of model will be very different.

The converse of the above, namely that the monitoring and source inventory requirements should be determined by a realistic assessment of the prediction capabilities of present-day models, is not generally addressed.

There is a basic incompatibility between point measurements of concentration and urban-scale model predictions for grid squares of the order of several km^2. One method of compensating for this effect is to develop sub-grid scale models such as street canyon models (Johnson et al (132) which predict the local influences of localized sources. Alternatively, the sampling stations should be selected so as to be representative of the grid-scale area within which the sampler is located.

Source Emission Sub-Model. The source inventory for the urban or regional model is a major undertaking, especially for models requiring time-dependent emissions. In general, detailed information is required on each of several hundred major point sources whose contribution needs to be treated individually, a network of line sources representing the major traffic sources in and around the city, and hundreds of area sources representing the aggregate emissions of hundreds of small sources within each area due to heating and local traffic sources.

Several comprehensive reviews on emission inventory methodology exist, including Hammerle (133) and Rossano and Rolander (134). For purposes of modelling, a given inventory may not provide the information in a form directly amenable to calculation, so that an emissions sub-model may be required. The sub-model generates emissions information, for each source specified in the model, corresponding to the time interval being modelled by applying a functional time-dependence to the standardized data stored on files.

Some of the emissions data may be in the form of production or process rates, in which case an emission factor (describing the total emissions from the source per production unit) must be applied in order to generate an emission rate. Similarly, emission factors are required for mobile source emissions determination from traffic and related data, and fugitive sources of particulates from exposed surfaces.

Meteorological Sub-Model. The requirement for a meteorological sub-model is determined by the type of model being developed. Numerical models generally are designed to accept spatially and temporally varying meteorological fields of wind and stability over a grid network. Since the data is obtained from a sparse network of recording stations, a program is required to generate the input data in the desired form for the transport and dispersion model.

The current methodology is to use interpolation methods on the observational data, but as meso-scale model becomes available, it is likely that these will be used to generate the required meteorological fields to the required degree of detail. The simplest models that require only a single wind determination for their application, do not require a meteorological sub-model.

2.5.5 Available Methods

The purpose of this section is to review the urban models developed for planning and predictive purposes and described in the literature. These models range from very simple analytical approaches to very complex numerical schemes incorporating chemistry and mesometeorology. In order to facilitate comparisons, Table 2-1 has been complied to classify the models in chronological order by the following categories:

TABLE 2-1

Urban Models Described in the Literature

Reference	Time Scale		Chemistry	Pollutants	Model Input	Application
	Short Term	Long Term				
Analytical Models						
Frenkiel (135)		✓		SO_2, CO	Climatological data	Los Angeles, Gaussian
Pooler (136) Pooler (137)		✓		SO_2	mean wind from 3 stations	Nashville, Tennessee St. Louis, Missouri seasonal averages Gaussian
Clarke (138)	✓			SO_2, NO_x	mean wind	Washington, 24-hour avg. Gaussian
Turner (139)	✓			SO_2	mean wind from 4 stations	Nashville, Tennessee 2-hour and 24-hour predictions Gaussian
Summers (140)		✓		TSP	mean wind, Temp Gradient	Montreal
Fortak (141)		✓		SO_2	Climatological	Bremen, Germany
Davidson (143)	✓			SO_2	mean wind	New York. Gaussian
Hilst et al (144) Bowne (145)	✓			SO_2,CO,NO_x	wind field from 10 stations	Connecticut regional model. Hourly concentrations. Gaussian
Koogler et al (146)	✓			SO_2	mean wind from 5 stations	Jacksonville, Florida 24-hour avg.
Miller and Hlozworth (147)	✓			SO_2, NO_x	mean wind	Nashville, Washington, Los Angeles. Gaussian
Ott et al (148)		✓		CO	climatological	Washington

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TABLE 2-1

Urban Models Described in the Literature

Reference	Time Scale Short Term	Time Scale Long Term	Chemistry	Pollutants	Model Input	Application
Panofsky and Prasad (149)	✓			TSP	mean wind from 5 stations	Johnstown, Pa.
Leahy (150) Leahy and Davies (151)	✓			SO_2	mean wind Temp Gradient	New York, Calgary.
Reiquam (152)		✓		SO_2	mean wind	Willamette Valley Box model
Roberts et al (153) Roberts et al (154)	✓			SO_2	wind field	Chicago. Integrated Gaussian Puff
Shieh et al (155)	✓			SO_2	wind field	New York City. Gaussian Puff Model
Bowne et al (156)	✓			SO_2, TSP	wind field	Toronto. Puff Model
Lamb and Neiburger (157)	✓			CO	wind field	Los Angeles. Lagrangian Puff
Martin (158)		✓		SO_2	climatological	AQDM. St. Louis. Integrated Gaussian Plume
Platt et al (159)	✓			CO, TSP	mean wind	Airport Air Quality Model
Zimmerman (160)		✓		SO_2	climatological	CDM
Gifford and Hanna (161) Hanna (163)	✓			SO_2,CO,TSP	mean wind	Integrated GAussian Plume. Applied to many cities in U.S.
Hanna (163)		✓		NO_x, O_3	mean wind	Los Angeles. Dimensional Box Model
Johnson et al (123)	✓			CO	mean wind	St. Louis, Chicago. Street-Canyon Sub-Model. Integrated Gaussian

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TABLE 2-1

Urban Models Described in the Literature

Reference	Time Scale		Chemistry	Pollutants	Model Input	Application
	Short Term	Long Term				
Start and Wendell (164)	✓			SO_2	wind field	Gaussian Puff
Lebedeff and Hameed (165)	✓			SO_2	mean wind	Nashville. Box Model
Porter and Christiansen (166)	✓	✓		SO_2 SO_2	mean wind climatology	TEM TCM
Praham and Christensen (167)		✓		SO_2	Climatological	Copenhagen. Gaussian Model
Turner and Novak (168)	✓			SO_2	mean wind	RAM
Petersen (169)	✓			SO_2	hourly met. data and emissions	PAL, small scale urban
Ludwig et al (170)		✓		CO	mean wind	St. Louis. Gaussian plus box
Numerical Models						
Randerson (171)	✓			SO_2	wind field	Nashville. Eulerian
Roth et al (172) Reynolds et al (173,174) Roth et al (175)	✓		✓	NO_x,O_3	wind field	Los Angeles. 3rd Eulerian SAI
Egan and Mohoney (176)	✓			SO_2	wind field	Eulerian. Moment-method
MacCraken et al (177) MacCraken and Sarter (178) MacCraken et al (179)	✓			CO	wind field	San Francisco LIRAQ

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TABLE 2-1

Urban Models Described in the Literature

Reference	Time Scale		Chemistry	Pollutants	Model Input	Application
	Short Term	Long Term				
Pandolfo and Jacobs (99)	✓			CO	calculated meso-meteorology	Los Angeles. Numerical meso-meteorology Model
Knox (180)	✓				wind field interpolated mass-consistent	San Francisco mulit-box
Shir and Shieh (181)	✓			SO_2	wind field	St. Louis, Missouri. Eulerian
Bankoff and Hanzevack (182)	✓			SO_2	wind field concentrations	Chicago. Adaptive-filtering model. Eulerian (Roth et al)
Bornstein and Runca (183)	✓			SO_2	URBMET meso-scale model	Venice. Linked PBL and K-theory model includes removal processes
Sklarew et al (184)	✓		✓	SO_2, O_3, NO_x	wind field	Used for Complex Terrain Situations. Eulerian-point source application
Eschenroeder and Martinez (185,186), Eschenroeder et al (187)	✓		✓	NO_x, O_3	wind field	Los Angeles. Lagrangian. DIFKIN
Weisburd et al (188) Wayne et al (189), Drivas et al (190)	✓		✓	NO_x, O_3	wind field	Los Angeles. Lagrangian REM and REM2
Sklarew (191)	✓		✓	CO, NO_x	wind field	MADCAP, San Diego. Langrangian
Sklarew et al (192) Sklarew et al (124)	✓		✓	NO_x, O_3	wind field	Los Angeles. Particle in Cell NEXUS

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TABLE 2-1

Urban Models Described in the Literature

Reference	Time Scale		Chemistry	Pollutants	Model Input	Application
	Short Term	Long Term				
Runca and Sardei (127)	✓			SO_2	wind field	Eulerian-Lagrangian
Christensen and Prahm (193)	✓			SO_2	wind field	Pseudo-Spectral Model
Lange (194) Lange and Sherman (195)	✓			Tracer	wind field using MATHEW	ADPIC. Combined Eulerian-Lagrangian Particle in Cell
Sheih (196)	✓			SO_2	wind field	Puff-Grid. PIC technique plus Puff
Statistical Models						
Peterson (197)		✓		SO_2	mean daily wind	St. Louis
Smith and Jeffrey (198)		✓		SO_2	temp & previous conc.	London
Bruntz et al (199)		✓		O_3	mean daily wind & temp solar radiation	New York
Caporaletti et al (200)	✓			NO_x,O_3	Concn's time series	San Diego
Zannetti (201)	✓			SO_2	Previous Air Quality	Venice, Italy. Real-time prediction on statistical basis

Time Scale

- short-term models are designed to simulate time-dependent concentration patterns for 1 hour to 1 day. These models require extensive meteorological and emissions data for their application.
- long-term models are desinged for evaulation of seasonal and annual air quality resulting from mean emission levels.

Mathematical Algorithm

- analytical models are those based on an analytical solution to a simplified diffusion equation. This category includes multi-source models whose basic computational kernel is an analytical solution.
- numerical models use the more basic equation of diffusion and attempt finite difference or equivalent methods of solution.
- statistical models apply multivariate analysis or similar techniques to generate predictions based on historical data.

Chemistry Sub-Model

- some numerical models incorporate chemistry sub-models aimed at determining the accumulation of the secondary pollutants.

Pollutants

- indicates the specific pollutants for which the model has been applied. This does not preclude the use of the model for other pollutants in the same category.

Model Input

- indicates the detail of the input meteorological data required to use the model.

Application

- location where model was first applied, and comments on model type or use.

It is common practice in air pollution modelling to apply a unique designation to models developed for a specific application even in cases where the algorithm was previously applied for a different model. Thus, the multiplicity of references in the Table does not reflect a similar multiplicity in methods of simulation.

Analytical Models. A majority of the analytical models for urban applications are based on the Gaussian plume model or the Gaussian Puff model.

i) Plume Models

The plume models simulate the urban sources in three categories:

a) Point Sources

The large emitters are treated individually as point sources. A submodel is used to determine the buoyant rise of the plume for the given meteorological conditions. These models are receptor oriented, with a calculation being performed for each source-receptor pair under consideration. The sum of all such contributions defines the concentration at the receptor.

b) Area Sources

The small sources, because of their number, cannot be treated individually. These are grouped into areas of several kilometres, and the total combined emission is assumed to be uniformly distributed over this area. The height of the emission is assumed to be the average height of the structures. The concentrations at the receptor are then determined by assuming a virtual point source upwind of the area contributing at a distance such that the spread of the plume at the location of the area source corresponds to the width of the area. An alternative method, the narrow plume hypothesis, has been developed to avoid this artificial procedure (Calder (202)), by integrating the individual contribution from each infinitesimal area source.

c) Line Sources

The dispersion of emissions from traffic sources is simulated by means of a line source. By integrating the point source plume formula for a series of source arranged in a line, an analytic representation of the concentration at a receptor is obtained in terms of the emission rate per unit length of the road. This is generally applied for the main traffic roads; the neighborhood streets are treated as an area source.

Calder (202) presents a general review of multiple-source plume models and of their structure. The line source component of the urban model is dealt with at greater length in the following section. The meteorological input to these models consists of mean wind, mixing height and stability for the area, and the dispersion is calculated for a steady-state condition and may be representative of several hours at a time or for 24-hours. Long-term averages are determined from a joint frequency distribution of a class conditions for wind and stability. This is used to weight the appropriate concentrations to produce the seasonal and annual average.

Early models of this type are those of Frenkiel (135), Turner (139) and Clarke (138). More recent examples are those of Porter and Christensen (166), Turner and Novak (168) and Prahm and Christensen (167).

ii) Puff Models

The Puff models are based on the instantaneous point source solution to the simplified dispersion equation. Puffs of given mass are released sequentially at a fixed time interval and advected with the local wind. The concentration at a receptor point is determined by integration of the contributions of all puffs released at previous times which affect the receptor. This model allows for the time-variation of meteorological parameters and for spatially-variable wind fields. This allows the model to provide more accurate short-term representation of the concentration pattern.

Because of the variable wind fields over the region, the relationship between the source and receptor is not as direct as for plume model. Consequently, a number of models resort to calculating concentrations for a regular grid network of receptors. This also facilitates the incorporation of long-term averages.

The flexibility of the puff model comes at the expense of enormously larger computing requirements than for the plume models.

Puff models were developed for New York by Shieh et al (155) for Chicago by Roberts et al (153), and for Toronto by Bowne et al (156). The Gaussian Puff model using interpolated mesoscale winds was applied by Start and Wendell (164). A Lagrangian Puff model of very general structure has been developed for Los Angeles by Lamb and Neiburger (157).

iii) Other Analytic Models

The models discussed in the previous sections are simple in the sense that the computing algorithm is simple; nevertheless, they require electronic computers to take into account the multitude of sources and receptors.

Some simplified models have been developed for purposes of urban simulation which can be applied without high-speed computer assistance. These include the model of the urban heat island and pollutant concentration for Montreal as developed by Summers (140) and similar models for New York by Leahy (150), and Calgary by Leahy and Davies (151).

Another method was used by Gifford and Hanna (161) which relies on the homogeneity of sources within the city. By using the Gaussian plume formula for area sources, and assuming analytical forms for the dispersion coefficients, and applying the narrow plume hypothesis, the concentration field is represented by a finite sum over the area sources. Martin (158) applied this technique for area sources and the Gaussian plume for the large point sources to simulate St. Louis air quality. This model then became the EPA AQDM model (Air Quality Display Model).

Gifford and Hanna (161) have shown that in the usual application, the grid square within which the receptor is located is the major contributor to concentrations at that receptor. Thus the sum over all area sources reduces to a single term, and the concentration is written in the form

$$C = AQ_o/u \qquad (2.5.12)$$

where u is the mean wind speed

Q_o is the average emission rate for the grid square where the receptor is located

A is a constant for a given city which can vary with stability.

It is found in practice that A is constant for a number of cities for which it has been tried. For short periods, this model does not account for the diurnal variability observed in concentration pattersn. Hanna (162) reports on a method by which this variability can be applied to A to produce more realistic short-term predictions.

The structure of the above model is essentially that of a Box model for each area grid square. A simple Box model was applied by Reiquam (152), and a more sophisticated one was developed by Lebedeff and Hameed (165) for application to Nashville. A combined Gaussian plus Box model was developed for St. Louis by SRI and applied to several cities (Ludwig et al (170).

Numerical Models. Models for urban problems have been developed on the basis of solutions to Eq'n. 2.5.6 with numerical integration techniques. Due to limitations of present-day computers, and the costs involved, most models impose some simplifying assumptions to make the task manageable. Generally these involve neglect of horizontal diffusion and vertical shear in Lagrangian models, and methods of reducting numerical diffusion in Eulerian schemes.

Liu and Seinfeld (230) have examined the errors involved in the two schemes for typical urban applications by comparing both schemes with analytic solutions for simple cases. In general, Eulerian models are more suitable for this application if the computational scheme can be made more accurate. This of course involves the use of finer resolution grids or other methods of reducing numerical diffusion (i.e., Boris and Book - see McCracken et al (1979).

i) Eulerian Models

The simplest Eulerian model assumes that the urban airshed can be divided into a number of boxes within which the pollutants are well-mixed. Pollutants are emitted into a given box and advected between boxes by the mean wind. Models of this type have been developed for San Francisco by MacCracken et al (177,179), and Knox (180).

The general approach is to solve Eq'n. 2.5.6. by finite difference methods including the diffusion term. Examples of this type of model include the model of Roth et al (172) developed for Los Angeles, Shir and Shieh (181) for St. Louis, and Egan and Mahoney (176) in which the moment method of reducing diffusion errors was developed. Pandolfo and Jacobs (99) developed a model for Los Angeles which incorporates a numerical meso-scale sub-model. Bornstein and Runca (183) have developed a linked PBL and diffusion model using the Bornstein URBMET model for Venice.

Bankoff and Hanzevak (182) have used the model of Roth et al (172) for Chicago, and added an adaptive-filtering sub-model which uses actual observational data to adjust model results at each computational step in order to improve the predictions for the next step.

ii) Lagrangian Models

Lagrangian models have been developed to avoid the pseudo-diffusion error of Eulerian Schemes; however, because of the complexity of allowing for general flows within the model, a number of simplifying assumptions are common, as noted above.

This type of model does have the flexibility of incorporating chemical transformations in a rather straight-forward way and has been used to study the Los Angeles smog problem. Models of this type have been developed by Weisburd et al (188), Eschenroeder and Martinez (185) and Sklarew (191).

iii) Other Models

Urban models have been developed incorporating other schemes for the solution of the diffusion equation. Thus, the Particle-in-Cell method has been used by Sklarew et al (192) for simulating the oxidant problem in Los Angeles and also by Lange (194) for San Francisco. Christensen and Prahm (193) have developed a pseduo-spectral method of solution of the diffusion equation which shows good accuracy.

More recently, Sheih (196) has developed a puff-grid model which combines the Particle-in-Cell technique with a puff sub-model which allows him to improve the resolution of the model so that it can be used for point and area sources.

In this model the large sources are treated as point sources by means of the puff model. When the individual puffs obtain a size equivalent to the grid spacing, they are integrated into the mass being carried by the grid cell. In this way substantial savings in execution time are possible, while maintaining the point source resolution required.

Statistical Models Statistical models rely on historical analysis of monitored data to derive their predictions. This places limitations on the applicability of such models since they are specific to the location at which they were developed and cannot be applied directly to another location. Their predictive power is also limited, in the sense that these models cannot be used to analyze the effect of changes in the source configurations, this being a primary requirement for the planning capabilities of urban models.

Early models of this type consisted of a correlation analysis of pollutant data with a selected number of meteorological parameters, the result being a regression-type of equation predicting the mean concentration for a given observational period. Among these models are those of Peterson (197) for St. Louis SO_2 levels, Smith and Jeffrey (198) for London SO_2 concentrations over a 24-hour sampling time, and Bruntz et al (199) for predicting ozone levels in New York city.

More recently, the approach has been extended to incorporate determinative equations into a statistical model, thus tuning the physical model by observed data. A model of this type is that of Caporaletti et al (200) for San Diego oxidant prediction.

A real-time predictive model of statistical type developed for Venice has been described by Zannetti (201). In this model, multiple regression of SO_2 levels on meteorological parameters is carried out. By time series analysis the model is continuously adapted to the most recent historical trends, and has been used to predict daily SO_2 averages.

Pollutant Transformation and Removal. In the urban environment, a number of polluting agents are present, giving rise to interactions which transform the primary pollutants such as NO and hydrocarbons into NO_2 and accompanying oxidants.

The interaction mechanisms can be very complex, and depend to a considerable extent on the ambient meteorology. Models have been developed to simulate these processes in the urban atmosphere and to predict the levels of the resulting secondary pollutants.

Most of this modelling has been concerned with the Los Angeles and Southern California problem. These include the models of Weisburd et al (188), Roth et al (172), and Eschenroeder and Martinez (185), as well as Sklarew (192) and Sklarew (191). A box model incorporating chemistry has also been proposed by Hanna (163). A detailed review of photochemicals models can be found in Eschenroeder (204).

Pollutants are also removed from the atmosphere by dry deposition onto surfaces and by wet removal by precipitation. For example, SO_2 half-life in the atmosphere could be as low as 3 to 6 hours. None of the urban models discussed is designed to take this effect into account in a realistic manner to the same level of detail as is done for the dispersion process.

2.6 Receptor Modelling

Receptor modelling is a recently developed technique of air quality source impact assessment. This technique is complementary to that of dispersion modelling, which was described in the previous section. Dispersion modelling begins with the source emission rate for a pollutant, applies a physical model of the atmosphere based on fluid mechanics to calculate the resultant concentration of the pollutant at any point (elevated or ground level) away from the source. Receptor modelling, on the other hand, beings with measured pollutant concentrations in ambient air. The connection between these concentrations and source emissions can be based on observed correlations with meteorological variables. In the case of wind direction, the familiar pollution rose is an example of such a correlation that can be used to resolve point source or other major contributions to pollutant loading at a sampling (receptor) site. Usually, however, the connection between specific sources and ambient particle loadings will depend upon detailed physical and chemical characterization of the particles. During the course of this study, airborne particulate matter was the pollutant of greatest concern, so further discussion of receptor models in this section will be limited to those for particulate matter.

Recent developments in receptor modelling of airborne particles have depended upon detailed physical and chemical characterization, as described in Section 2.4. Such data are necessary to resolve source contributions to ambient airborne particle loadings when many sources are responsible. This resolution is sometimes referred to as source apportionment.

Physical characterization, as already described, has been based mainly on microscopy. In this approach, optical or electron microscopy is used to examine the morphology and optical properties of particles collected on a filter. This technique was used to advantage in the 14-city assessment of urban particlate matter in the U.S. (40). More recently, sophisticated microscopy techniques have been combined with chemical characterization to carry out source apportionment studies (35,36). In brief, particles from a source or source category are characterized by such phenomena as size, shape, crystal structure (or lack of it) and optical properties. The approximate relative contribution of that source or category of sources to the particle loading in an ambient sample is determined by observing the relative number and mass of characteristic particles of the appropriate type that make up the collected sample. Physical receptor models have not been widely applied, but in the hands of skilled microscopists are a valuable means of assessing source contributions to ambient particle loadings.

Chemical receptor models have developed rapidly during the past ten years and have been applied with increasing frequency to source apportionment studies. Recent review of this field by Throgmorton and Exetell (37), Cooper and Watson (206), and Gordon (207) and a recent conference (208,209) and workshop (210) have summarized the state of the art. The development of chemical models, of course, was dependent upon reliable chemical analysis of ambient particulate matter and source emissions. Trace chemical analysis of environmental samples has only in the last ten to fifteen years reached the levels of sensitivity and quantification necessary to justify the use of detailed receptor models.

Multi-element analysis and more recently analysis of ions and molecular species in airborne particulate matter have been applied to receptor models in a number of different ways. All of the sampling and analytical techniques mentioned in Section 2.1 have been exploited in these applications. Cooper and Watson (206) have categorized chemical receptor model applications into the following types: chemical element mass balance, enrichment factor analysis, time series correlation, multivariate models and spatial models. The earliest identified published work in each of these areas is in the time period 1976 to 1971. Of these, chemical element mass balance or chemical mass balance (CMB) for short, was chosen to be used to assist in interpreting the data from the Hamilton study.

Each of the various types of receptor model would have to be described in detail in order to explain the rationale for this choice. Basically, the CMB method is the only receptor model that makes direct use of detailed chemical composition information in connecting specific sources or types of sources with ambient particle loadings. One of the multivariate techniques, target transformation factor analysis (TTFA) (66), is essentially equivalent to CMB (206).

The principle of the CMB approach is very simple. Any sample of ambient airborne particulate matter in a urban area is made up of contributions from many sources. If the detailed relative chemical composition of the particles emitted by each contributing source (source profile) is known, and the same data are available for one or more ambient particulate matter samples (receptor profile), the CMB model provides a means of calculating the proportionate contribution of eac source to each sample.

Conceptually, the CMB method works as follows. The relative compositions or chemical profiles (in weight percent or equivalent units) of the source emission for as many elements or other chemical components as possible can be combined with appropriate weighting factors to give the best representation of the measured composition of an ambient particulate matter sample (also in weight percent, etc.). The weighting factors in this best representation are the relative (percent) contributions of emissions from a given source to the particle loading at a given sampling site. These relative contributions can then be used to calculate by simple arithmetic parameters such as the number of micrograms per cubic meter a source contributes to the loading at a sampling site.

The formalism of the CMB method is presented in detail in Section 3, but will be discussed briefly here to introduce the technique. If a set of chemica compositions or other properties are determined for a number of source emissions and a receptor particulate sample, the relative contributions of each source type can be calculated from a set of linear algebraic equations, providing that the number of sources or source types used is less than or equal to the number of chemical properties.

The CMB method computes the set of weighting coefficients that produces the best match between the set of source chemical profiles and the receptor chemical profiles. This fitting is accomplished by a regression technique. These best-fit coefficients give the relative source contributions directly.

There are several problems which detract from the achievement of quantitative source apportionment. Two of these problems are major. Seldom are all of the sources that contributed to an ambient particulate sample known. In addition, emitted particles from most sources have not been characterized thoroughl enough to yield reliable chemical composition profiles. In many cases in which measurements have been made, the source or receptor sampling or analytical methodology has been limited in sensitivity or number of chemical components covered, so that chemical composition profiles have lacked the completeness necessary for optimum CMB calculations.

The lack of quantitative source characterization (including both point sources and fugitive sources) makes it difficult to use the CMB method to resolve sources with similar chemical profiles. Quite often, such sources are lumped together in a so-called component of typical or average chemical composition. A typical CMB calculation would apportion the observed receptor particulate matter sample into contributions from a relatively small number (5 to 10) of source types or components. These components might represent a single source, such as an isolated, nearby coal-fired generating station or a generic source such as "soil" or "iron and steel industry".

The most complete applications of the CMB technique have been made by Cooper and co-workers (206), who studied the Portland, Oregon aerosol and Gordon and co-workers (207), who have studied the Washington, D.C. aerosol. Both groups based their CMB calculations on detailed locally measured source profiles. Recently, a group working at General Motors Research Laboratories achieved a nearly quatitative chemical mass balance on the Denver, Colorado aerosol (212) during winter. That is, essentially the entire measured airborne particulate matter loading in two size fractions was accounted for by the measured chemical elements, compounds and ions, without reference to their source(s). This has not been achieved before. The CMB source apportionment being carried out on the Denver aerosol by Dzubay and co-workers at the U.S. EPA (62) has been able to resolve only six generic source components so far, however. Dzubay has reviewed the application of CMB to dichotomous sampler data in particular (213).

Although many of the point emission sources in Hamilton have undergone source testing programs in recent years, only total particulate matter loadings have been measured in most cases. This means that source chemical profiles for Hamilton-area sources were not available in the detail required for CMB calculations on the airborne particulate matter samples. For this reason, source profiles typical of the specific types of sources in Hamilton, but determined from measurements made elsewhere, had to be used to complement the Hamilton specific data in the CMB calculations.

Since the primary objective of the study was to determine the contribution of street dust and other local sources of ambient airborne particle loadings relative to the major traditional (industrial) sources, the resolution of contributions from individual, traditional point sources was not proposed to be an essential result of the study. In this context, the CMB approach is seen to be a reasonable choice as an efficient and sufficiently accurate treatment of the chemical data base generated during the project. Section 5 includes a detailed discussion of the application of the CMB gechnique to the Hamilton data base as a means of identifying the major sources of airborne particles at the study sampling sites.

The participation of Dr. J.A. Coooper of NEA, Inc., one of the leading proponents of the CMB method, in the analyses and interpretation of the CMB data was a major contribution to this aspect of the study.

2.7 Studies of Road Cleaning Effects on Urban Particulate Loadings

2.7.1 Introduction

The failure of many urban airshed to meet ambient air quality standards for particulate matter (Section 2.2) has motivated studies to characteri urban airborne particles and identify their sources (Section 2.4). Typically, control strategies have been developed through an analysis of the contribution of traditional sources of particles. Urban particulate matter studies have generally shown that non-traditional sources of urban particles frequently contribute a significant fraction of the observed TSP. The soil component (part of which is made up of road dust) is often the highest, ranging from 20% to 40% of the TSP. Thus it is reasonable to anticipate that a potentially viable approach to reducing the urban TSP is to reduce the quantity of available particles for reentrainment from roads by means of a street cleaning program.

Street cleaning methods fall into two categories:

- street sweepers
- street flushers.

Three basic types of sweepers are in use. The most common is a rotating gutter broom that moves materials from the gutter area into the main pickup broom, which rotates to carry the material onto a belt and into the hopper. A second class of sweepers uses a regenerative air system. These sweepers are designed to "blast" the dirt from the road surface into the hopper. A third, vacuum sweepers, has been in use in Europe for many years. These vacuum sweepers use both a broom for loosening and moving street dirt and a vacuum system to pick up the debris. Removal efficiency of the sweepers vary in a wide range from sweeper to sweeper and from city to city.

A street flusher consists of a water supply tank mounted on a truck or trailer, a gasoline engine driven pump for supplying pressure, and three or more nozzles for spreading the water as directional sprays. The large nozzles on the flusher are individually controlled. Street flushing strives only to displace dirt from the street surface to the gutter. The volume of water used is insufficient to transport litter to the nearest drain. Should flushing result in transport into the drain, additional loading of suspended and dissolved solids into the receiving waters of the storm sewer system would result.

It is estimated that 80 - 90% of the total mass of road dust accumulates within about 30 cm of the curb (214). Hence most of the street cleaning operations concentrate on this area. A survey of street cleaning practices in ten selected cities in the U.S. showed that the average efficiency of road dust removal was around 50% (215). Road dust removal efficiency depends on the tpye of cleaner, the passing speed, the number of passes and frequency of cleaning, and on the particle size.

Debris and large particles (above 100 μm in size) are very effectively removed (70 - 80%). However, smaller particles are much less efficiently removed and may even show an increase in mass following cleaning due to break-up of larger particles. Street flushing serves asthetic purposes and moves material to the gutters.

There have been relatively few studies reported in which the effect of street cleaning methods on observed urban TSP was determined. Most of these studies were not published but were summarized in a report prepared for the U.S. Environmental Protection Agency which was issued in 1977 (216). The following outlines the results of these studies.

2.7.2 Street Cleaning Studies

Twin Falls, Idaho. This study was carried out over a three month period in the summer of 1973. HiVol samplers were operated at nine locations; three downtown, four suburban, and two rural. Streets in the downtown area were cleaned once a week on Mondays (and Tuesdays if not completed on Monday). Suburban areas were cleaned on an irregular basis and the rural sites were at least one mile away from street cleaning activity.

The downtown and rural site data were compared with respect to relative concentration profiles as a function of day of the week. The assumption made was that the influence on observed relative TSP figures by factors such as traffic density, meteorological parameters or variable source strengths of particles is the same at all sites studied. If this assumption is valid, then differences in the relative concentration profiles between downtown and rural sites would indicate a street cleaning effect. No data were presented to support this assumption and it is not clear whether it was appropriate.

The results were not statistically compared but it was judged that the weekly variation in concentration at the two rural sites was essentially the same as at the downtown sites. The conclusion was that street cleaning was ineffective in reducing TSP in Twin Falls.

Chicago, Illinois. This study was conducted in 1974 over a one month period. Four HiVol samplers were located in the downtown area near the street. A fifth sampler was located at a downtown site considered to be much less affected by road dust. Two of the group of four samplers were in an area which was swept daily, while the other two were swept every other day.

It was assumed that the average TSP within the group of four sites would be the same in the absence of any difference in street cleaning activities, and also that any difference between the fifth site and the group of four was due to road dust only. No data were obtained to support these assumptions.

Average TSP data over the study period showed about the same results within the group of four sites, while the fifth site had a lower TSP by about 55 $\mu g/m^3$. It was concluded that there was no noticeable effect of an increase in street cleaning frequency from alternate days to daily on TSP levels and that road dust contributed at least 55 $\mu g/m^3$ (about 50% of the TSP) to each of the four sites.

New York, N.Y. Two commercial/business districts were studied over a period of two years (9 months in Newark and 15 months in Brooklyn). HiVol samplers were operated over 4-hour periods throughout the day. Traffic counts and meteorological data were also collected. The samplers were mounted four meters above street level and three meters back from the curb.

During the late summer and fall, periods of daily street flushing were carried out for a total of 15 days (three in Newark and 12 in Brooklyn). Thus, periods of short-term cleaning were created which could be compared with the more extensive non-cleaning periods.

Differences between the average TSP levels observed for these periods were atributed to the effect of cleaning operations. Implicit in this analysis was the assumption that other variables, such as short and long-term meteorological conditions and seasonal variations in particle source strength, were not significant. It seems unlikely that this assumption is appropriate and no data were presented to support it.

The results showed an average reduction in TSP of about 16 $\mu g/m^3$ (∿ 15%) on days when flushing was carried out compared with those days when no flushing was done. It was therefore concluded that flushing of streets produced a reduction in TSP of about 15%. The statistical significance of this is unclear.

Kansas City, Kansas. Prior to 1976, mechanical sweeping was used in this city to clean the downtown central business district daily, major streets and industrial areas weekly, and most residential areas monthly. In 1976, a street flushing program was initiated on the same schedule as sweeping such that the cleaning operation consisted of flushing followed by mechanical sweeping.

Data from three HiVol samplers were collected for the period of 1972 - 1976 when only mechancial cleaning was carried out and during the street flushing period. In addition, data from 12 other urban and suburban sites in the area (where no changes in street cleaning had occurred during 1976) were also collected. Average TSP figures for the group of three and 12 sites during the first three quarters of 1976 were compared with similar averages during the previous four years.

The results showed a decrease in TSP levels over previous yeras in the first two quarter of 1976 for both groups of sites followed by little change in the third quarter and an increase in TSP during the fourth quarter. Since changes in the observed TSP for both groups of sites during 1976 were similar, it was concluded that the street flushing program in the subregional area where it was performed was not effective in reducing TSP levels. This conclusion relies on the unsubstantiated assumption that average TSP variations between the two groups of sites should be the same in the absence of different street cleaning methods. The required data to test this assumption and establish the conclusions on a statistical basis appear to be available but the appropriate analysis was not carried out.

Charlotte, North Carolina. Between 1973 and 1976, street cleaning in Charlotte was gradually changed from mechanical broom sweepers to regenerative air units. By 1976, downtown areas were cleaned daily and all major arterials twice per week.

HiVol data were collected for urban sites potentially affected by street cleaning over the period of 1971 to 1976. In addition, similar data were collected from HiVols located in nearby suburban and rural sites where it was judged that the impact of reentrained road dust and street cleaning would be small. Trends in observed average TSP levels for both groups of sites were analyzed for the six year period.

The results showed a decrease in TSP levels over the period at both groups of sites. This decrease was judged to be similar and hence not attributable to street cleaning techniques. The conclusion that changes in street cleaning methods had no effect on TSP relies on the assumption that trends in relative TSP levels for both groups of sites should be the same in the absence of differing road dust contributions.

Cincinnati, Ohio. This study was designed to evaluate three cleaning methods - flushing, mechanical sweeping and vacuum sweeping. The study area was a five by seven block region in downtown Cincinnati within which each cleaning method was evaluated. Each was carried out over a one month period for a total of three months, plus one additional month with no cleaning as a control period.

Cleaning cycles during the periods were irregular but consistent (early in the first week, not at all in the second, twice in the third, and once in the fourth week). HiVol samplers were located at seven sites within the study area and operated daily. In addition, seven regional HiVol samplers were operated on a six day cycle within a four mile radius of the study area.

The results for the study area were averaged and the TSP levels ranked according to cleaning method used. The data indicated that the highest average TSP levels were observed during the period of no street cleaning. TSP levels during flushing were the next highest, followed by vacuum sweeping. Mechanical sweeping resulted in the lowest average TSP levels observed within the study area.

Based on these results it was concluded that mechanical sweeping is the most effective method in reducing TSP from road dust. This conclusion depends on the assumption that changes in the monthly average TSP levels during the four month study period can be attributed to the effects of street cleaning only. There is no support for this assumption. In fact, the regional site monthly average TSP levels reported in this same study show significant variations during the four month period even though they are well outside the study area. When the study area data were adjusted by subtracting the corresponding data from the regional sites, it was then found that mechanical sweeping appeared to be the least effective method while vacuum sweeping became the most effective. Clearly, other parameters are dominating the variations in TSP levels observed during the period and none of the street cleaning methods used appear to be effective enough to produce statistically significant reductions in TSP levels.

Kansas City, Missouri - Urban Area Study. The experimental design of this study was similar to the study described above for Cincinnati. Mechanical sweeping and flushing were compared within a four by seven block area located in a commercial/warehouse district. Mechanical sweeping was carried out for four weeks, flushing for three weeks, and no cleaning for five weeks. The frequency of each cleaning method was once per week.

HiVol samplers at seven sites within the study area were operated on a daily basis as well as three sites located in suburban areas five to six miles from the study area. The suburban sites were intended to serve as controls. In addition, fifteen HiVol sites, which are part of a regional network, provided data on a six day cycle.

A comparison of average TSP data for the two cleaning methods and the period of no cleaning show flushing to be the most effective method. If the study data are adjusted by subtracting the control data for corresponding periods or, alternatively, subtracting regional station data, then it is concluded that flushing is effective in reducing TSP, while mechanical cleaning is not.

This study suffers from the same problems that the Cincinnati study does.

There are other parameters, such as variations in emission strengths of particle sources and meteorological conditions, which strongly affect the observed TSP level and the experimental design does not adequately allow corrections to be made for these factors. Reliable conclusions cannot be drawn from the data presented.

Kansas City, Missouri - Residential Area Study. This study was specifically directed towards residential areas in Kansas City. Since most previous studies of the effects of road cleaning on TSP were concentrated on urban areas, it was seen as desirable to determine whether the regular use of vacuum sweepers on low traffic density residential streets results in improved air quality.

Two HiVol samplers were used in the study. One was located in a residential suburb of Kansas City within which all of the streets were cleaned about once a week with a vacuum sweeper; the other was located in an adjacent residential community where street cleaning was less frequent and was carried out using mechanical sweepers. An effort was made to place both samplers in comparable exposures.

It was assumed that, in the absence of different street cleaning methods and frequencies, both sites would have the same TSP levels. Thus any differences in TSP levels between the sites could be attributed to the effect of vacuum cleaning over mechanical cleaning. This essential equivalence of the two sites was not verified by a base line study, however.

Sampling was carried out on alternative days at both sites for a four month period. A statistical analysis of the data showed that the observed TSP at both sites was not significantly different. The conclusion was that vacuum street cleaning in the test area did not result in a significant improvement in air qualit as judged by TSP levels.

2.7.3 Summary

The results of the field studies and control measure evaluations were variable and inconclusive. None of the cleaning methods were judged to be effective in all of the studies in which they were tested. Where a cleaning method was judged effective, the statistical significance was unclear. The results can be summarized as follows:

Cleaning method	Studies in which method was judged effective	Studies in which method was judged not effective
Broom Sweeping	1	2
Vacuum Sweeping	0	2
Regnerative air sweeping	0	1
Flushing	2	2
Sweeping and Flushing	0	1

All of the studies reviewed suffer from serious experimental design faults which prevent a proper statistical evaluation of the significance of the results. Urban aerosol characterization studies have shown that reentrained particles are frequently a major contributor to urban TSP levels and road dust may be expected to form a significant portion of this particle source (Section 2.4). Parameters such as meteorological conditions, site proximity to local sources, and influencing topographic features can exert strong effects on the observed TSP. These parameters were not adequately accounted for in the street cleaning studies reported.

Most of the studies evaluated the effectivenesss of street cleaning by comparing observed TSP levels during the street cleaning periods against expected TSP levels in the absence of cleaning. The expected TSP levels were inferred from data gathered at the test site during a different time period or, alternatively, from data taken during the test period at other locations. In either case, the temporal or spatial variability in TSP levels must be accounted for in the comparison. Failure to do this reduced the sensitivity of the experiments to detect the influence of street cleaning on TSP.

2.8 Control Strategies

In the past, fugitive particulate emissions were considered to be only a nuisance, in that such emissions would increase soiling and reduce visibility in the vicinity of the source. It was generally thought that the dust generated consisted mainly of large particles which would easily settle out a short distance downwind and not become suspended in the atmosphere. However, Cowhard and coworkers (217) found that a significant percentage of the particles were below 30 μm in diameter, i.e. in the TSP size range.

Control agencies have become increasingly concerned with fugitive particulate emissions and their control. This concern is due to a number of factors, but most importantly because of non-attainment of air quality objectives for ambient TSP levels in many jurisdictions largely because of uncontrolled fugitive emissions, and also due to an increasing emphasis on controlling fine particles in the inhalable size range (< 15 μm).

2.8.1 Development of Control Strategies

The development of an air pollution control strategy designed to attain and maintain ambient air quality criteria or objectives requires an analysis of current and possible future air quality problems. The quantitative and qualitative procedures used in developing an acceptable plan for the control of fugitive dust have been described by the U.S. EPA (218). A summary of the strategy development is given below. The amount of work involved in each step will vary from area to area depending on such factors as available data, magnitude of the problem and types of emission sources. The steps involved are:

- A review of air quality monitoring data to characterize the nature and extent of the suspended particulate problem. This includes an assessment of the representativeness of each monitor site by characterizing the general and site-specific areas around the monitor, identifying local factors which exert an influence on the measured TSP levels, and establishing a history of these local influences and their anticipated status in the near future. This assessment will give an indication whether local or areawide sources need to be controlled. The suspended particulate problem can then be characterized by statistical analysis of patterns in air quality data, with particular emphasis given to the apparent relationship between meteorology and TSP levels, and to trends at various sites.
- The development of a baseline particulate emissions inventory for sources which may be significantly affecting the problem area.
- The formulation of an emissions/air quality relationship by evaluation of alternative source-receptor models.

- The characterization of alternative control measures for application to significant fugitive dust sources.
- The selection of a control strategy and evaluation of the impact of the strategy on air quality. This is accomplished by selecting a control measure for applications to each of the major source categories and specific areas which are the cause of high TSP levels in a problem area. The proposed strategy is then evaluated by using control effectiveness data to estimate emission levels resulting from the strategy, and the air quality model to estimate resulting air quality. The cost of the proposed strategy is estimated along with the problems associated with its implementation. A demonstration strategy can be considered as a first step in the development of the total strategy.

The first three steps of this strategy development have been described elsewhere (Sections 2.2 to 2.6). The types of control measures available for non-traditional sources and how they might be implemented in a strategy are reviewed briefly in the following Sections (2.8.2 and 2.8.3).

2.8.2 Available Control Measures

Unpaved Roads and Areas. Control methods to reduce dust emissions from unpaved roads and areas consist of:

- paving
- application of chemical stabilizers
- watering
- traffic-related controls

The cost-effectiveness of each of these methods has been assessed (218,219). Paving decreases the total amount of dust being generated, but it has been shown that paved roadways can themselves be significant sources of fine particulate matter (220).

Application of chemical stabilizers is a very effective dust suppressant (218), but provides only temporary control and can be quite expensive depending on the particular stabilizer used.

Watering is the most common method of dust suppression. However, this also is only a temporary dust control measure and often is not effective (218).

Traffic controls offer potential for dust emission reductions from unpaved roads, however, this measure is probably not realisable in a large urban area.

Entrained Street Dust. Reentrained street dust has been found to consist primarily of mineral matter similar to common sand or soil, mostly tracked or deposited onto the roadway by vehicles, but also includes engine exhaust, particles from wear of brake linings and bearings, and from abrasion. Two principle control approaches have been used:

- control of street dust origins
- street cleaning.

Significant origins consist of carryout of dust from dirt surfaces by motor vehicles, atmospheric fallout of airborne particulates, and transport from adjacent exposed areas. Since most of the streets in the Hamilton study area also have curbs and gutters, the major control of dust transport from adjacent exposed areas would be by vegetation along sidewalk areas and removal of dirt carried onto the road by vehicles.

Construction and Demolition Activities. Construction activities are temporary and variable in nature. Fugitive emissions arise during the activities (e.g. excavatio vehicle operation, equipment operations) and as a result of wind erosion over the exposed earth surfaces.

Wetting the surfaces of vehicle access roads to sites is an effective control provided the surface is maintained wet. However, this causes problems due to the carryout of mud onto adjacent streets. The carried out mud dries and becomes dust again and is susceptible to vehicular resuspension. Street cleaning the becomes necessary.

Wind entrainment from exposed soil surfaces can be minimized by a combination of two control actions (2). First, a soil stabilizer, such as a chemical or vegetation, may be applied. A second control action involves stipulating the period during which construction occurs.

The major control action used at demolition sites is watering.

Agricultural Operations. Techniques for controlling fugitive dust from agricultural areas include:

- continuous cropping with limited field exposure
- crop residue management and modified tilling operations
- limited irrigation of fallow fields
- windbreaks and stripcropping
- chemical soil stabilizers.

A discussion of the effectiveness of these methods is included in reference (218).

Other Sources. Other fugitive dust sources would be tailing piles, storage piles, and disturbed soil surfaces. Control measures for these sources include application of chemical stabilizers, watering and the use of wind-breaks. Wind-breaks, either natural or artificial, can be used for almost any non-industrial source depending on the particular application.

2.8.3 Integration of Control Measures into Overall Strategy

Strategies developed for areas that are significantly affected by both traditional and non-traditional dust sources should reflect the application of control measures on both types of dust sources. The chosen control measures should provide control in an expeditious and practical way.

Evaluation of Control Strategy. The emission levels that will result after implementation of control measures should be estimated for both a target year of attainment and for projections which take account for growth of new emission sources. The data base required for such estimates is obtained through control efficiency information (218,219) for various dust control measures in addition to baseline and projected emissions inventories.

After choosing a set of appropriate control measures, a control strategy is selected by means of an iterative process in which control alternatives are successively tested using a source-receptor model to predict resulting air quality levels. The final strategy is that which attains the air quality objectives using the most cost-effective combination of available control measures.

The overall control strategy should reflect the degree of control necessary to attain air quality objectives over both 24-hour and annual averaging periods. This in turn depends on which of the two primary objectives for particulate air quality (annual or 24-hour) is the more restrictive. This can be determined by comparing the geometric standard deviation (GSD) of sampling data to the GSD of the objectives (71). The GSD of the objectives is the slope of the line of a log-probability plot passing through both the 24-hour and annual standards. This slope will vary with the proposed sampling schedule. If the GSD of the sampled data is greater than the GSD for the objectives, the 24-hour objective is more restrictive, and vice-versa for the annual objective. In general, the annual objective is more restrictive.

The cost of implementing control measures varies widely from area to area, thus local cost data should be obtained. The total cost of applying the control strategy is expressed in terms of cost effectiveness and compared to other measures currently used under existing regulations. Another important consideration in assessing costs is the time frame available for implementation of controls.

Factors Affecting Control Measures Selection. The technical and economic feasibility of various controls will differ depending on a number of factors which differ from area to area. These are:

- the compatibility of the controls with the overall goals and plans for the area. For example, the paving of roads and improvement of road shoulders is compatible with long-term city development objectives in the area of transportation improvements. Thus, the compatibility adds to the larger general technical and economic feasibility for control measures because of other desirable benefits they provide.
- the degree of control required. The higher the level of control needed to meet objectives, the greater is the potential for technical and economic demands to be the determining factor in selecting a control strategy.
- the financing mechanisms available for implementation. The source and ease of funding for any control alternative should be identified and evaluated. Some controls will be funded by taxes,

while others will be paid for by industry.

- the social acceptability of the control strategy. A demonstration project, as part of the first phase of implementation, may be used to generate public support when necessary.
- the timetable for implementation.

Strategy Implementation. The implementation of a control strategy is governed by the technical, political, legal and socioeconomic constraints associated with the various control measures. The magnitude of these constraints, in turn, depend on the general approach to implementation of the strategy, that is, whether it is to be enforced as a series of air pollution control regulations, or as concurrent actions to be taken by various agencies in the performance of related projects. While the former approach is required for several source categories, the latter approach, which operates through binding agreements on the part of several agencies that they will participate in and be responsible for the implementation of a certain portion of the strategy, offers benefits. This approach achieves greater political and social acceptance since the measures are viewed not only as air pollution controls, but as overall planning and development improvements that will yield several benefits in addition to air quality improvement, and is particularly appropriate for control of the major fugitive dust emission sources which are largely uncontrolled at present.

A major obstacle to implementation of a fugitive dust control strategy, whichever approach is used, can be from the socioeconomic acceptability of the proposed actions. Clear justification for additional expenditures associated with the control strategy must be given. The use of a demonstration project as the first phase of a strategy can facilitate justification of the strategy by showing its benefits (218).

The strategy to control particulate matter should be a comprehensive one which integrates the control of fugitive dust, stack emissions, industrial process fugitive emissions and other area sources. Such a strategy has the greatest probability of reducing ambient TSP levels.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

3. EXPERIMENTAL PROGRAM

The experimental program was designed to develop quantitative knowledge on the contributions of various sources and source categories to urban TSP levels in the City of Hamilton. In order to provide such information, studies were undertaken to define the relative importance of non-traditional sources at various locations within the city. Attention was focussed on the following areas:

- the characterization of the physical and chemical composition of several size fractions of the suspendable portion of urban dust
- determination of the effects of independent variables such as meteorology, traffic patterns and urban characteristics on the extent of reentrainment
- the evaulation of available control technology (i.e., road sweeping).

Thus, the study encompassed several different objectives and was divided into several different experiments.

3.1 Scope of the Study

The study was carried out at seven monitoring sites in the Hamilton area. As shown in Figure 3.1, sites were located along Cannon Street, a major artery in downtown Hamilton situated between the heavy industrial area and the downtown core, and two of these were chosen as the major sites for experimental activities. One of these latter sites, designated the Experimental site, was used to assess various street cleaning methods and other studies to define more precisely the contribution of road dust to measured TSP levels. The other site, designated the Control site, was used for control studies. The two sites were selected to be as similar as possible, and the studies conducted at the Control site permitted allowance to be made for variations in industrial emissions, meteorological conditions and other uncontrolled variables during the course of the studies. The two other sites on Cannon Street, one near the intersection with John Street (John St. site), and the other near the intersection with Oak Avenue (Oak Ave. site), were used to assess the variation in TSP levels along the street. In addition, three other monitoring sites were operated outside the downtown area

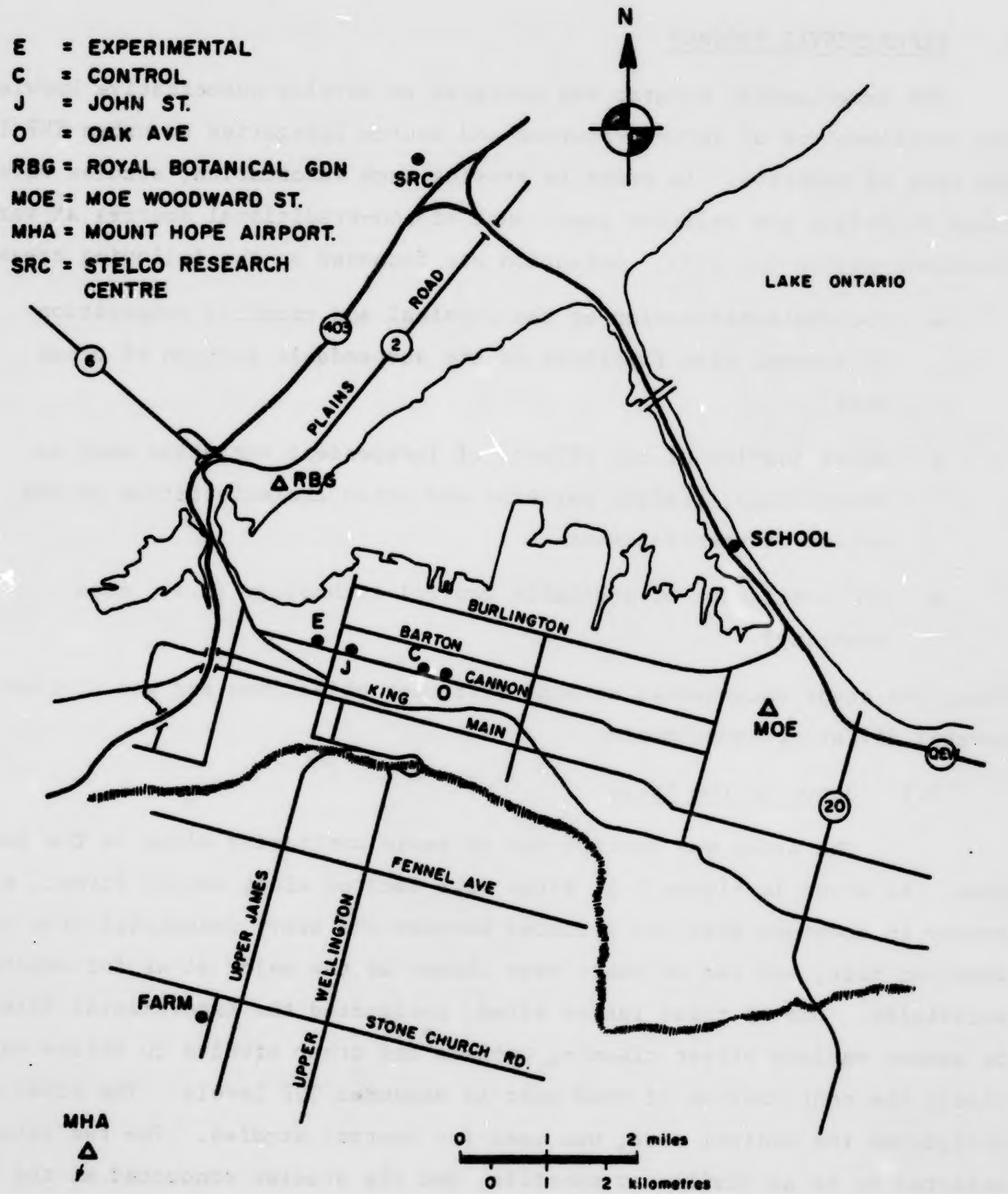

E = EXPERIMENTAL
C = CONTROL
J = JOHN ST.
O = OAK AVE
RBG = ROYAL BOTANICAL GDN
MOE = MOE WOODWARD ST.
MHA = MOUNT HOPE AIRPORT.
SRC = STELCO RESEARCH CENTRE
N
SRC
LAKE ONTARIO
403
2
ROAD
PLAINS
6
RBG
SCHOOL
W
BURLINGTON
E
BARTON
J
C
CANNON
O
KING
MAIN
MOE
QEW
20
FENNEL AVE
UPPER JAMES
UPPER WELLINGTON
FARM
STONE CHURCH RD.
MHA
0
1
2 miles
0
1
2 kilometres

FIGURE 3-1 MAP OF HAMILTON AREA

to establish overall background TSP levels and assess regional and long-term transport effects. The sites were located at Bell Cairn Memorial School in the Beach Boulevard area (School site), at Stelco Research Centre (SRC) situated across the harbour to the north of Hamilton (SRC site) and at a farm situated on West Fifth Street south of the intersection with Stonechurch Road (Farm site) on Hamilton Mountain. Also shown in Figure 3.1 are the locations of the meteorological stations from which data was used in evaulation of the results.

TSP levels were monitored at all sites using HiVol air samplers. At the Experimental and Control sites, the variation of TSP levels with height above the ground was monitored and, in addition, the variation of TSP levels with distance away from the street was monitored at the Experimental site.

Carbon monoxide (CO) levels and coefficient of haze (COH) were monitored at the Experimental and Control sites and traffic counters were operated at the major roads near these sites.

Particulate characterization studies were conducted using automated dichotomous samplers. The operation of these samplers is described later. Their basic principle is to sample suspended particulate matter of less than 15 μm aerodynamic diameter and separate this material into two fractions; a coarse fraction of aerodynamic diameter particles from 15 to 2.5 μm size and a fine fraction consisting of particles with aerodynamic diameter of less than 2.5 μm. Two of these samplers were used, one at each of the Experimental and Control sites.

An experiment was conducted at the Experimental site which was designed to assess the actual raod dust contribution to TSP levels. A tracer compound was applied to the road surface and the suspended particulate matter was collected at two monitors, one near the edge of the road and one some distance back from the road, using cellulose filters. By analyzing for the tracer compound, along with other elements, an assessment of the road dust contribution could be made. The cellulose filter monitors, however, were run continuously from July 16 to September 7 in order to obtain samples of ambient particulate matter on a filter substrate suitable for chemical analysis.

The experimental segment of the study was conducted from June 10, 1979 to September 7, 1979 and was divided into three periods. The first period (June 10 to July 7) was used as a baseline study to define normal variations in TSP levels. During the second period (July 8 to August 7) a continual road sweeping program around the Experimental site using mechanical sweepers was carried out. During the third period (August 8 to September 7) a similar road sweeping program using vacuum sweepers was conducted. At several times during the sweeping periods, samples of road dust were collected from the road surface at each of the four Cannon Street sites. Dustfall samples were taken at the Experimental and Control sites to correspond with these periods.

An overall schedule of the various parts of the experimental program is illustrated in Figure 3.2. Each of the separate phases of the program are describe fully below. The detailed results of each component of the study are summarized in a Set of Appendices bound separately from this report. Copies of these Appendices are on file with Environment Canada and the Ontario Ministry of the Environment.

3.2 Microinventory Methodology

3.2.1 Introduction

In the context of this study, a microinventory is an orderly compilation and quantitation of particulate sources in the vicinity of an air sampling site. Its purpose is to consolidate information on source emissions or activity rates, monitor siting, air quality data and land use characteristics into a consistent format and data base. This can then be used to assist in identifying sources of particulate matter close to the monitoring site. Such information can subsequently be used to interpret observed differences in air quality at various monitoring sites, and thus establish the relative importance of the contributions of various sources in the study area to the observed suspended particulate loadings

The methodology and results described below was used to:

- establish that the Experimental and Control sites are relatively similar
- flag anomalies at or between different sites for further evaluation
- give a first approximation of the relative impacts of various sources
- validate the effects of local sources, particularly by height/distance relationships.

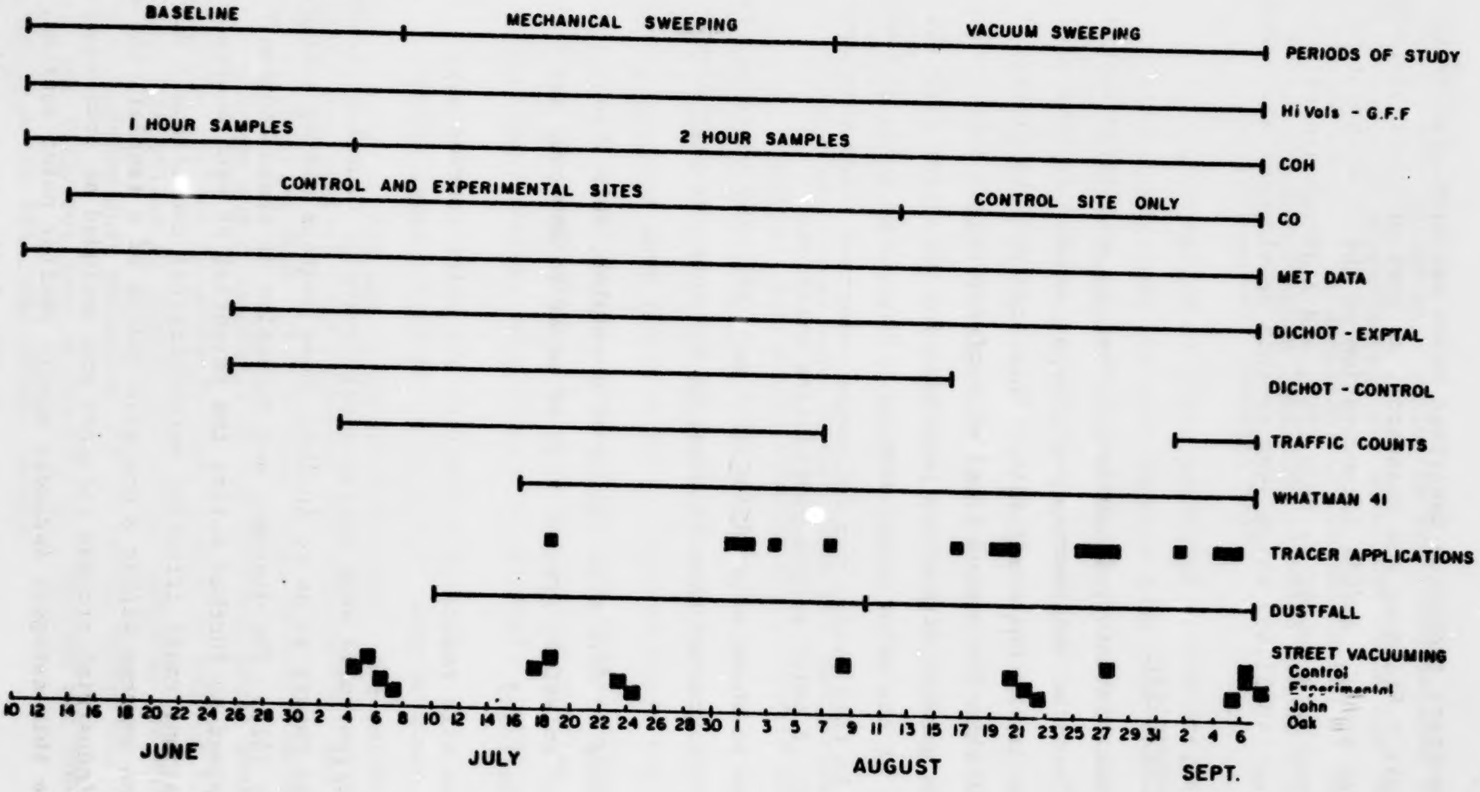


FIGURE 3-2 DATA BASE FOR HAMILTON ROAD DUST STUDY.

The microinventory technique described below was developed by the U.S. EPA, Office of Air Quality Planning and Standards, as part of particulate analyses in several EPA regional areas. A full documentation of the development of the methodology can be found in a report by Pace (51), and a discussion of the results of various U.S. studies (40,55,65) which lead to this development are presented above.

3.2.2 Methodology

A microinventory is conducted over an area large enough to include the location of most of the sources believed or assumed to have significant effects on TSP air quality at the study site. This area will be different for elevated point sources than for ground level or roof-top height emissions of area sources because of the greater dispersion potential for emissions from the taller stacks characteristic of the major point sources. Since both point and area sources had to be considered in this study, the following selection rules were applied in compiling an inventory of point source particulate emissions:

a) Within a one to three mile radius of a sampler, only those sources with emissions greater than or equal to 100 tons per year were included.

b) Within a three to five mile radius of a sampler, only those sources with emissions greater than or equal to 250 tons per year were included.

c) Within a one mile radius of a sampler, all point sources were included.

These selection rules were chosen after review of Gaussian dispersion model applications and theory so as to include those sources having a significant effect on air quality (51). The distance and direction of these sources from a monitor was also obtained to further define the potential of each source to influence TSP concentrations under different meteorological conditions. Within the last category, for the sources within a one mile radius of a sampler, the emissions were combined in an industrial process category and included as area sources. This was done because this category includes mostly smaller point sources.

For area sources, an area within a one mile radius of a sampler was inventoried (51). A one mile radius is specified because dispersion modelling shows that this is approximately the area over which low level sources will have a significant effect. In addition, the larger number of small sources, their diversity of shapes and broad land area coverage making a listing similar to the above for point sources very impracticable.

In consideration of these practical restraints, an inventory technique was used which apportioned the area sources into nine annular sectors in four directions and three distances from the monitor as depicted in Figure 3.3. Sector 1 included all area sources within a quarter-mile radius of a monitor, and Sectors 6-9 included all sources from within a half-mile to a mile radius of a monitor. In addition, the distance and average daily traffic (ADT) levels of roadways within 200 feet from the monitor were recorded. Separate tabulations were made for area sources within each of the nine sectors.

The area sources were divided into two categories of combustion and fugitive dust sources. Combustion sources included were residential, commercial and industrial fuel combustion, incinerators, automobile and diesel truck exhaust emissions, railroad diesel emissions and emissions from shipping. Fugitive dust sources inventoried were railroad yards, unpaved roads and laneways, unpaved parking lots, unpaved storage areas, aggregate storage areas, cleared or exposed areas, construction and demolition sites, agricultural activities and reentrained street dust. The latter source, reentrained street dust, proved to be the dominant area source.

Particulate emissions in tons.yr^{-1} were obtained for each of the sources mentioned above by the use of emission factors. The emission factors used in this inventory were derived from published EPA factors (54) and from recent studies of sources of fugitive dust (51,218) with suitable modification to reflect the special features and climatology of the Hamilton study area. These emission factors were applied to activity factors such as vehicle miles travelled (VMT) and acres of land tilled to compute emissions estimates for each sector. The factors used for fugitive dust emissions are listed in Table 3-1. Derivations of these factors are fully outlined in Appendix A. Factors for combustion emissions are obtained from the EPA compliation (54,221).

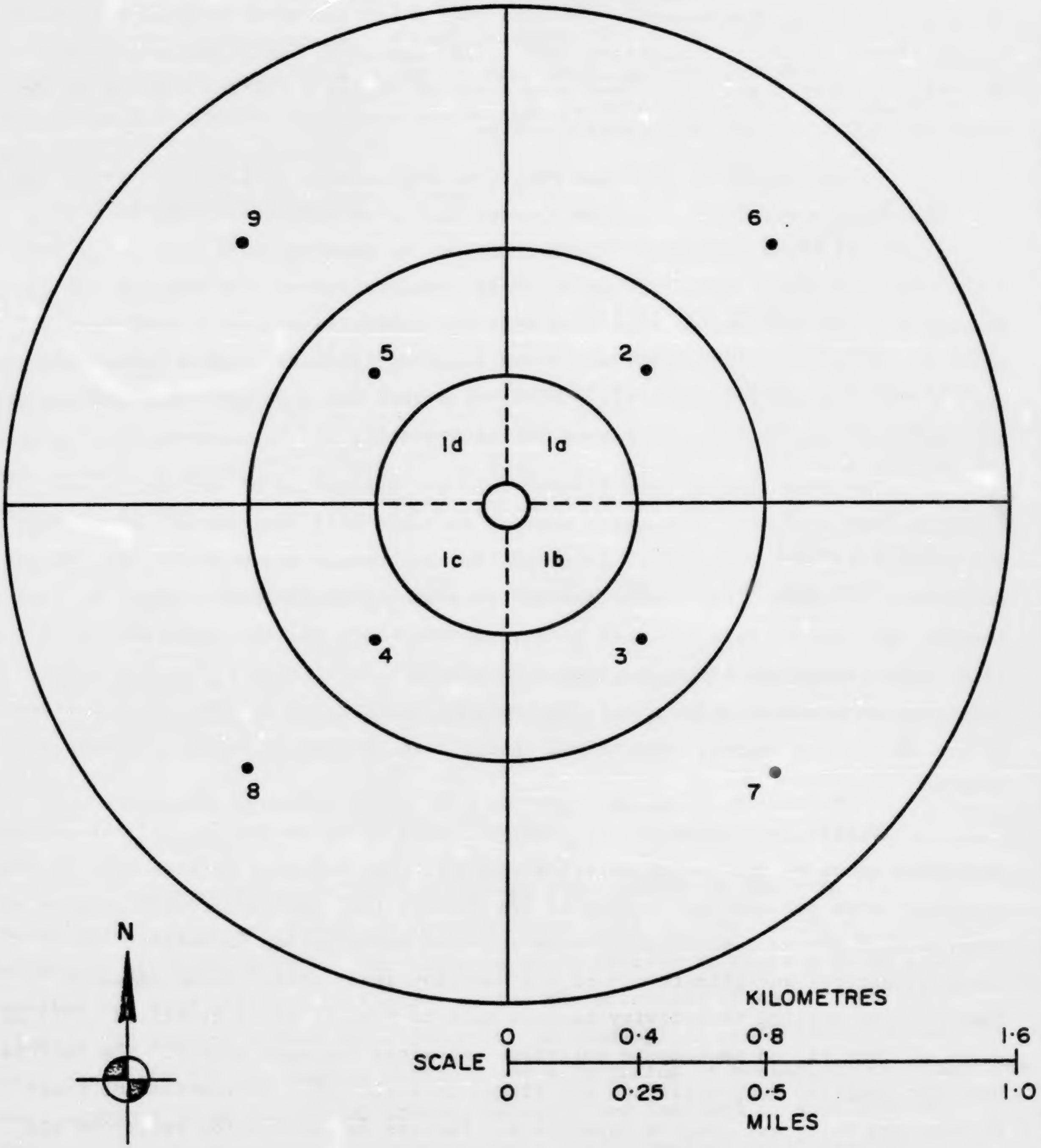

9
6
5
2
Id
Ia
Ic
Ib
4
3
8
7
N
KILOMETRES
0
0·4
0·8
1·6
SCALE
0
0·25
0·5
1·0
MILES

FIGURE 3 - 3 STANDARD SECTORS USED IN MICROINVENTORY

TABLE 3-1

Fugitive Dust Emission Factors
For Hamilton Microinventory

Source Category	Emission Factor	Units
Railroad yards	0.10	ton/acre/yr
Reentrained dust		
- auto traffic	3.15	g/VMT
- diesel truck traffic	6.78	g/VMT
Unpaved roads	3.00	lb/VMT
Cleared or exposed areas	0.06	ton/acre/yr
Construction/Demolition	0.28	ton/acre/yr
Agriculture	0.02	ton/acre/yr
Aggregate Storage	2.10	ton/acre/yr
Slag piles	0.50	ton/acre/yr
Unpaved parking lots	1.50	lb/VMT
Unpaved storage areas	0.20	ton/acre/yr
Coal Storage	0.97	ton/acre/yr

3.2.3 Data Collection Procedure

To minimize the time required for the field survey, some types of information relevant to the microinventory compilation were obtained beforehand:

i) Topographical maps (1:25000 scale) of the Hamilton area marked with the Universal Transverse Mercator (UTM) 1 km squre grid, were obtained from the Ontario Ministry of Natural Resources (222). These maps were used to locate point sources within the UTM coordinate system and hence calculate their distance and direction from each monitoring site.

ii) Street maps (1 in. - 100 ft. scale) of Hamilton were obtained to cover 1 mile radius areas around each monitoring site. These maps were marked with a 200 m square UTM coordinate grid in order to locate area sources and distinguish the different sectors around each site. The maps were copied and the copies used in the field for location of fugitive dust sources.

iii) Aerial photographs of the Hamilton area were obtained from the Ontario Ministry of Natural Resources (223). These were used to locate cleared areas, particularly in the remote background sites, and to give a visual presentation of the area around each monitoring site.

iv) A compilation of point source emissions for the Hamilton study area was obtained from the Ontario Ministry of the Environment (224). Each source is located by street number and UTM coordinates in this compilation along with its associated emissions. These data were used with the topographic maps mentioned above to locate each source with respect to the monitoring sites.

v) A compilation of area source emissions for the Hamilton study area was obtained from the Ontario Ministry of the Environment (225). This compilation lists the combustion emissions for each area source within 1 km square UTM grids across the Hamilton study area. Emissions were estimated using EPA factors. Types of area sources included were residential, commercial and industrial fuel combustion (coal, residual oil, distillate oil or gas), incinerators, auto and diesel truck exhaust (tire wear is also included here for convenience), railroads and shipping. These data were used with the street maps mentioned above to apportion area source emissions to each sector of monitoring site-specific inventory.

vi) Two forms of traffic data were obtained from the City of Hamilton Traffic Department. The first of these was in the form of a traffic map showing the average daily traffic (ADT) for each of the major streets in Hamilton. This was used to verify the auto and diesel truck exhaust emissions obtained from the area combustion source inventory mentioned above. The second form of traffic data was traffic counts obtained during the study period on Cannon, Bay and Victoria Streets in Hamilton, all roads in close proximity to the two major monitoring sites. These counts were used to calculate the locally generated traffic dust as discussed below.

A visual inspection was made of the area within the 1 mile radius around each monitoring site. (Descriptions of the sites are included in Section 3.3). This required two people in the field for one to two days per site, either on foot or in a car depending on the particular site. The condition of the streets as to whether they were paved or unpaved, the amount of dust in lanes, the presence of curbs, etc., was described and recorded on maps. The location, area and activity of unpaved or gravel parking lots was estimated and recorded. In addition, any cleared areas, construction/demolition sites, agricultural tilling or railyards were recorded. Fugitive dust emissions for the different types of sources were estimated using these data as outlined in Section 4.1.

Area sources were assigned to each sector as follows: the proportion of each microinventory sector within a particular 1 km square UTM grid was estimated. Then a proportionate amount of the emissions for each source within each 1 km square UTM grid were assigned to that sector. This was done for each sector within the 1 mile radius area around each monitoring site. The summaries for all monitoring sites are included in Appendix B.

Using data from the topographic maps (222), the distance and direction from each monitor to each large point source was calculated and tabulated. The tabulations for each monitoring site are included in Appendix B. Table 3-2 lists the 1974 emission data for major point sources, this being the most recent data available at the time of conducting the microinventory. Figure 3-4 shows their location with respect to the monitoring sites.

The distance of each monitor from the nearest curb of any adjacent roadways within 200 feet was recorded and tabulated with the corresponding ADT count for each roadway. Tabulations of each monitoring site are also included in Appendix B.

TABLE 3-2

Listing of Point Source Emissions of Suspended Particulate Matter used in the Microinventory

No.	Name	Description	1974 Emissions (tons/yr)
1	Canron Ltd.	Ferrous Foundry	131.2
2	Stelco Steam Plant	Steam Plant	102.1
3	Stelco Blast Furnace	Blast Furnace Stoves	702.6
4	Stelco Coke Quench	Coke Quenching	160.6
5	Stelco Sinter Plant	Sinter Plant	1512.6
6	Stelco Coke Ovens	Coke Ovens	1025.8
7	Stelco Coke Handling	Coke Handling	490.6
8	Stelco B.O.F.	Basic Oxygen Furnaces	496.4
9	Stelco Open Hearth	Open Hearth FCE, Hot Metal Transfer	885.5
10	Proctor & Gamble	Fuel Combustion, Spray Drying	258.9
11	Dofasco B.O.F.	Lancing, Tapping & Charging	1241.0
12	Dofasco Coke Ovens	Coke Ovens, Batteries & Quenching	727.4
13	Dofasco Blast Furnace	Stoves & Casting	494.7
14	Dofasco Coke Ovens	Coal Handling, Coke Ovens, Batteries	618.2
15	National Steel Car Co. Ltd.	Wood Mill, Shot Blasting	98.8
16	Interflow Systems	Thermal Degradation	200.00

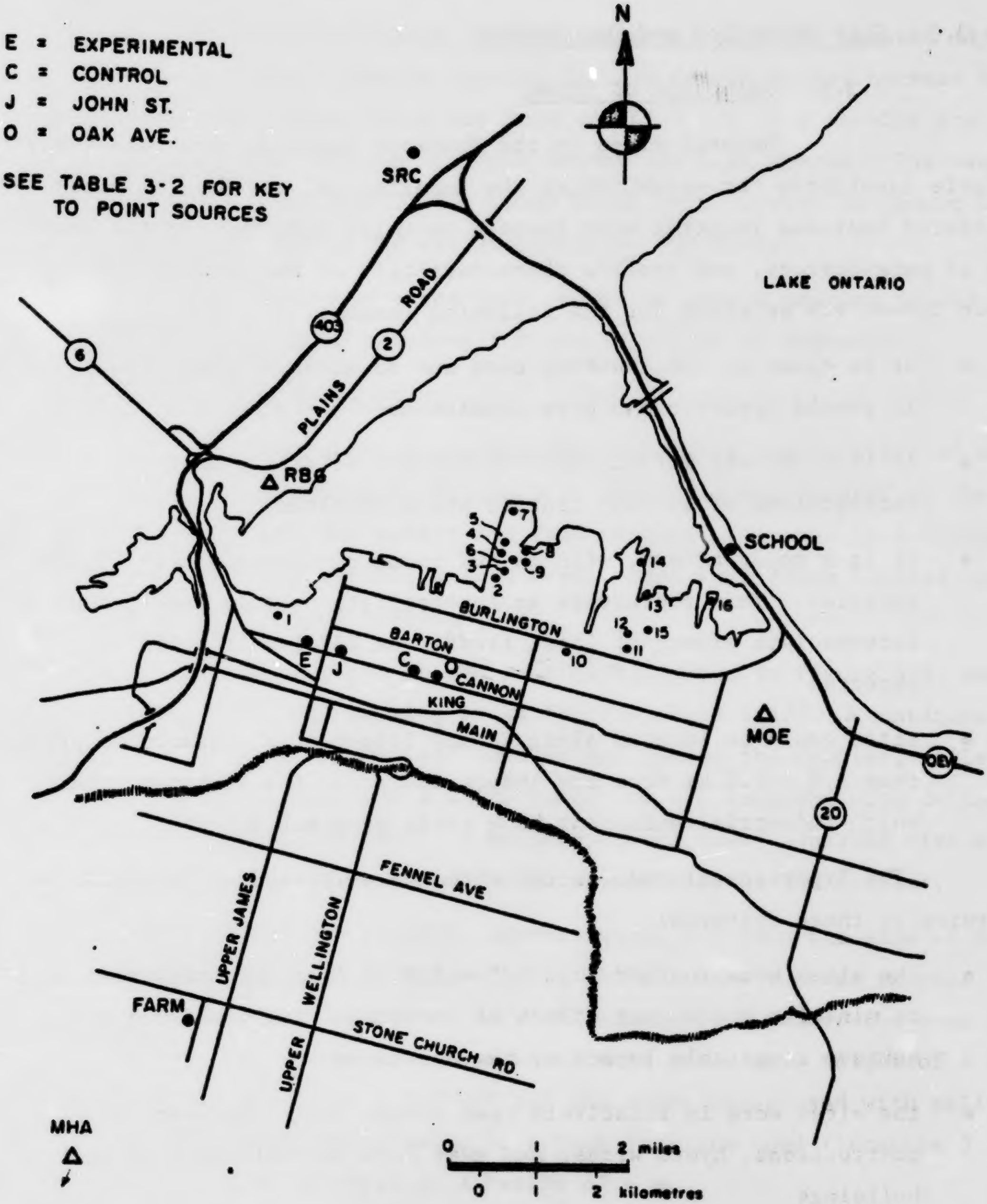

E = EXPERIMENTAL
C = CONTROL
J = JOHN ST.
O = OAK AVE.
SEE TABLE 3-2 FOR KEY TO POINT SOURCES
N
SRC
LAKE ONTARIO
6
403
2
PLAINS ROAD
RBG
SCHOOL
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
BURLINGTON
BARTON
E
J
C
O
CANNON
KING
MAIN
MOE
QEW
20
FENNEL AVE
UPPER JAMES
UPPER WELLINGTON
FARM
STONE CHURCH RD
MHA
0 1 2 miles
0 1 2 kilometres

FIGURE 3-4 LOCATION OF MAJOR POINT SOURCES.

3.3 Site Selection and Description

3.3.1 Selection of Sites

Several sites in the downtown Hamilton area were inspected as suitable candidates for establishing the Experimental and Control sites. Factors considered included location with respect to major industry and the downtown core, type of neighborhood, and traffic characteristics of the nearest roadway. Cannon Street was selected for the following reasons:

- it is close to the downtown core and so sites located along it should typify urban core conditions
- it is a one way street, thus turbulence effects caused by interactions of two-way traffic are eliminated
- it is a major artery, with an ADT count of approximately 15,000 vehicles. This represents an intermediate traffic level, thus an intermediate effect of local traffic on TSP levels could be expected
- sites could be located along Cannon Street at a distance of greater than 1.5 - 2.0 km from the industrial area, the distance within which industrial emissions have their greatest impact.

The Experimental and Control sites were located on Cannon Street according to these criteria:

- the sites were further than 1.5 - 2.0 km from the industrial area to minimize the direct effect of industrial emissions and to achieve comparable impact at the two sites
- the sites were in relatively open areas, free from overhead obstructions, hydro wires, and away from the influence of tall buildings
- the sites were in light commercial or residential areas so that no local point sources could unduly affect TSP levels
- the sites were far enough apart that any experimentation carried out at the Experimental site would not affect the Control site, but close enough together that all other influences were as similar as possible.

From these considerations, the Experimental site was located adjacent to an open area (a service station parking lot) on Cannon Street between Bay Street and Park Street. The Control site was located similarly in a service stations parking lot on Cannon Street between Victoria Street and East Avenue. The two sites were approximately 1.5 km apart. Two other sites were located on Cannon Street as described below to assess TSP variations along the street.

The three background sites were chosen so that a measure of TSP levels in incoming air masses could be obtained for any direction of approach.

3.3.2 Site Description

Experimental Site. A map showing the immediate vicinity and location of the Experimental site is presented in Figure 3-5. The site was located on the north side of Cannon Street, between Bay Street and Park Street. The area is a mixture of residential and light commercial, with a scrap metal yard being located approximately 20 m west of the main sampling site.

A trailer was located at the site as indicated in Figure 3-5, and this was used as one of the main working areas for the field staff. A continuous CO monitor and a continuous COH monitor were housed inside the trailer, while an automatic dichotomous samper and a HiVol (used for air sampling with cellulose filters) were located on the roof. A meteorological tower equipped with a U2A anemometer at 7 m above ground, was attached to the side of the trailer.

Located beside the trailer, approximately 3 m from the edge of the street, was a 15 m tower (location 1 in Figure 3-5). HiVols were mounted on this tower at 4 m, 8 m and 15 m heights. A tower was also located 33.5 m from the road (location in Figure 3-5) and two HiVols were mounted on this tower at a height of 4 m, with one being used with glass-fibre filters and the other being used with cellulose filters. A further tower was located 61 m back from the road (location 3 in Figure 3-5) with a HiVol mounted at a height of 4 m.

A dustfall jar was mounted on the meteorological tower beside the trailer. Traffic counters were installed on Cannon and Bay Streets as illustrated in Figure 3-5.

Figure 3-6 shows photographs of the site. Figure 3-6a shows a view of the trailer and the 15 m tower. The meteorological tower, dichotomous sampler and

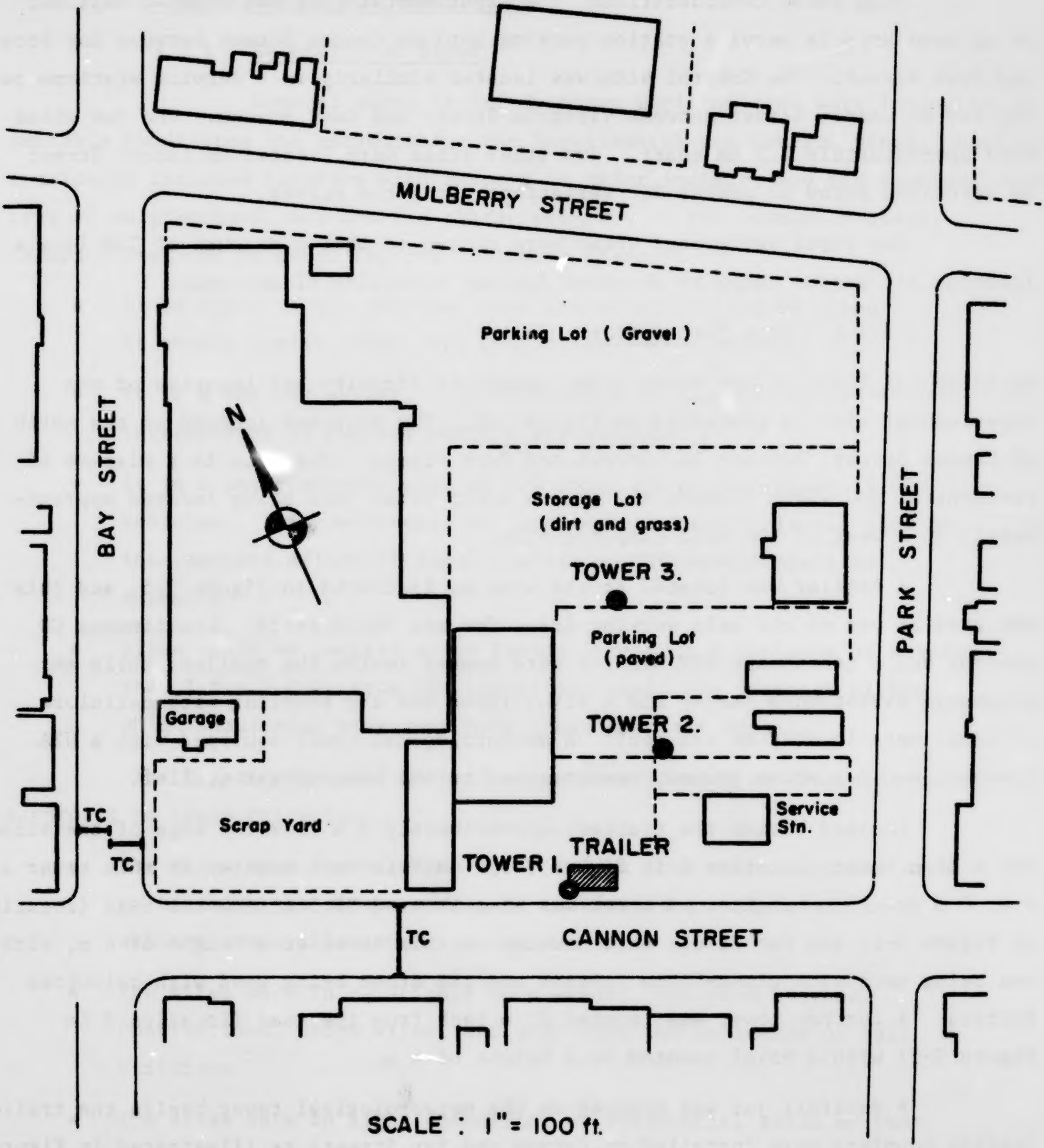

MULBERRY STREET
BAY STREET
PARK STREET
CANNON STREET
Parking Lot (Gravel)
N
Storage Lot
(dirt and grass)
TOWER 3.
Parking Lot
(paved)
TOWER 2.
Garage
Scrap Yard
TC
TC
TC
TOWER I.
TRAILER
Service Stn.
SCALE : 1" = 100 ft.

FIGURE 3 - 5 EXPERIMENTAL SITE

FIGURE 3-6a: View of Trailer and Tower-Experimental Site

FIGURE 3-6b: Experimental Site-View of Off-Road Tower

the twin HiVols on the tower 33.5 m back from the road can also clearly be seen. Figure 4-6b shows a view of the two towers at 33.5 m and 61 m from the road.

Control Site. A map showing the immediate vicinity and location of the Control site is presented in Figure 3-7. The site was located on the north side of Cannon Street, between Victoria Avenue and East Avenue, in the parking lot of a service station. The area is predominantly residential in character.

A trailer was located at the site as indicated in Figure 3-7, and this served as the second main working area for the field staff. As for the Experimental site, a continuous CO monitor and a sequential tape COH monitor were housed inside the trailer, with a second automatic dichotomous sampler being located on the roof. Also located on the roof of the trailer was an MRI meteorological instrument for continuous monitoring of wind speed, wind direction and ambient temperature.

Located beside the trailer, approximately 3 m from the edge of the road, was a 15 m tower. HiVols were mounted on this Tower at 4 m, 8 m and 15 m heights, as for the Experimental site. A dustfall jar was mounted on a hydro pole located approximately 5 m east of the 15 m tower, and traffic counters were installed on Cannon Street and Victoria Avenue as shown in Figure 3-7.

Figure 3-8 shows photographs of the site. Figure 3-8a shows a view of the trailer and 15 m tower, and the dichotomous sampler and anemometer assembly can be seen on the roof. Figure 3-8b shows a view looking west down Cannon Street from this location.

John Street Site. A map of the John Street site is presented in Figure 3-9. The site was located on the north side of Cannon Street, between Hughson and John Streets. The area, a mixture of light commercial and residential properties, is situated between the Experimental and Control sites, approximately 800 m east of the Experimental site. One HiVol was mounted at a height of 4 m on a lamp standard located at the southwest corner of a service station lot, approximately 3 m from the edge of Cannon Street. Figure 3-10 shows a photograph of the site.

Oak Avenue Site. A map of the Oak Avenue site is presented in Figure 3-12. The site is located on the north side of Cannon Street, between Oak Avenue and Smith Avenue, approximately 400 m east of the Control site. A HiVol was mounted at a height of 4 m on a hydro pole located approximately 30 m east of Oak Avenue and 1 m from the edge of the road. The area is predominantly residential in character. Figure 3-11 shows

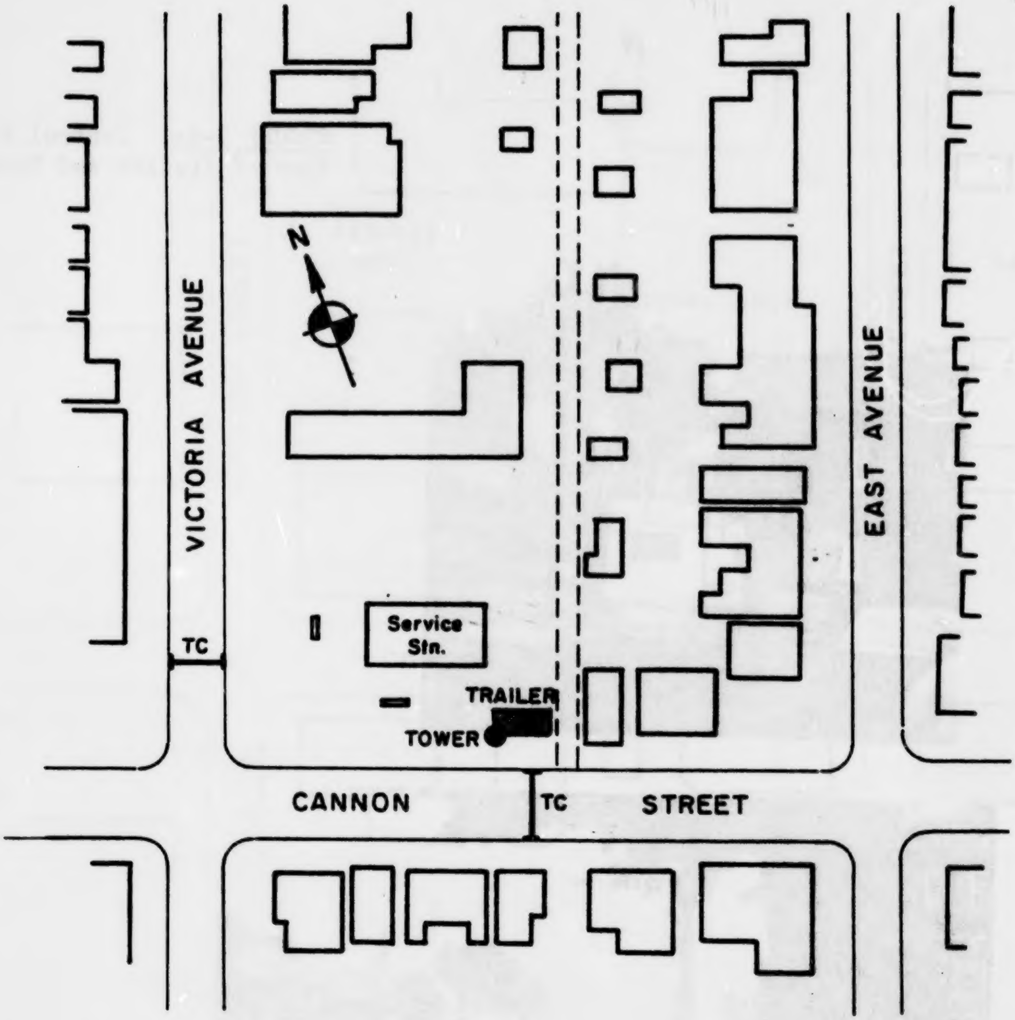

N
VICTORIA AVENUE
EAST AVENUE
Service Stn.
TC
TRAILER
TOWER
CANNON
TC
STREET

FIGURE 3-7 CONTROL SITE

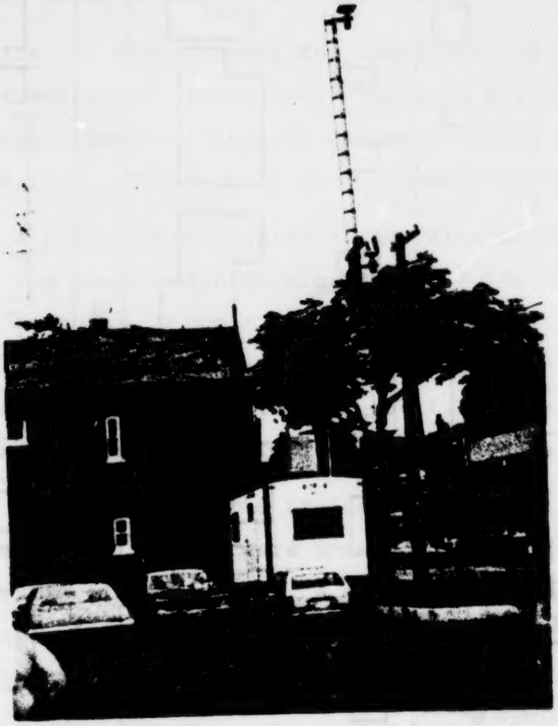


FIGURE 3-8a: Control Site View of Trailer and Tower

FIGURE 3-8b: Control Site-Looking West Down Cannon Street

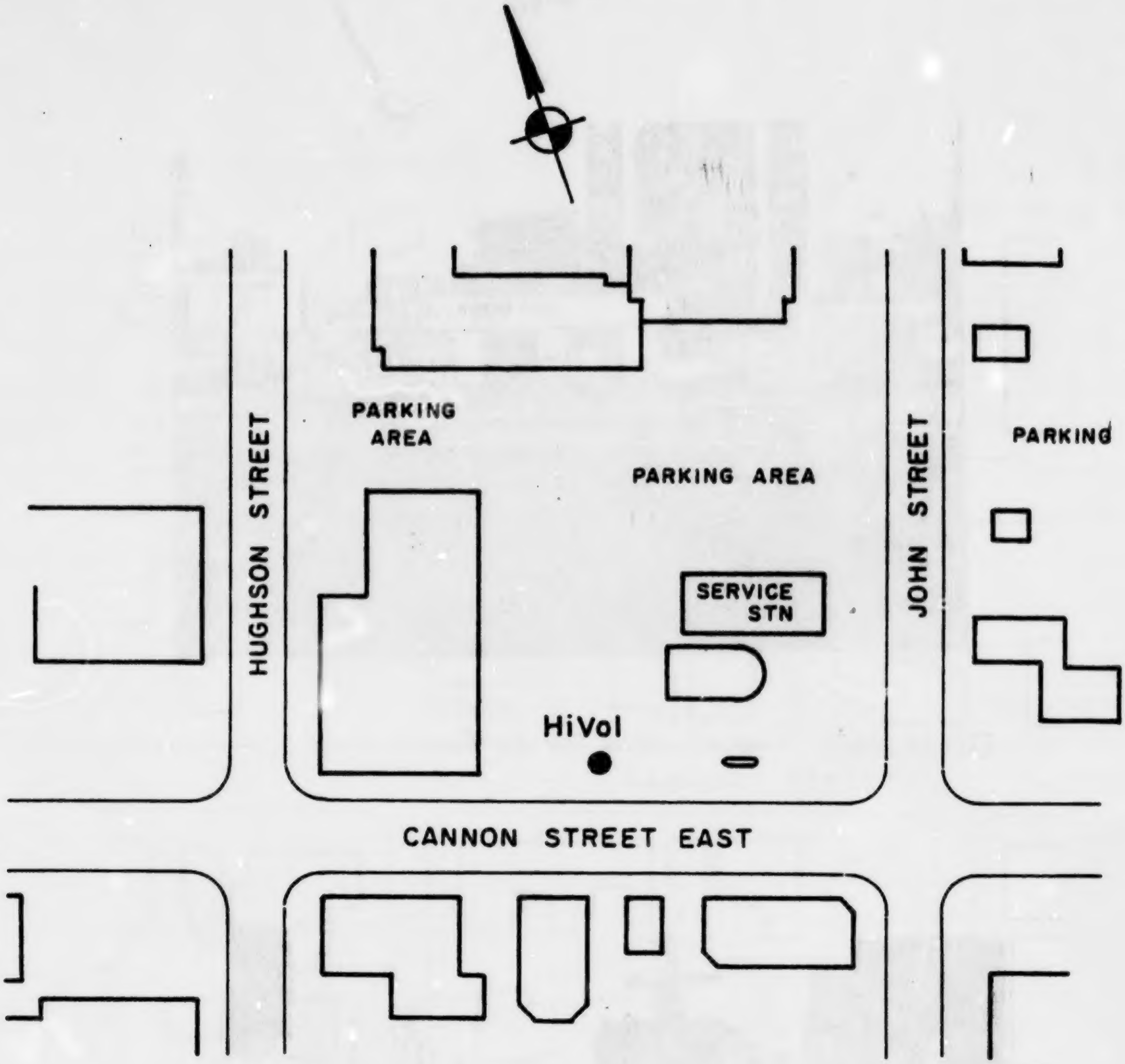

PARKING AREA
PARKING
PARKING AREA
HUGHSON STREET
JOHN STREET
SERVICE STN
HiVol
CANNON STREET EAST

FIGURE 3-9 MAP OF JOHN STREET.

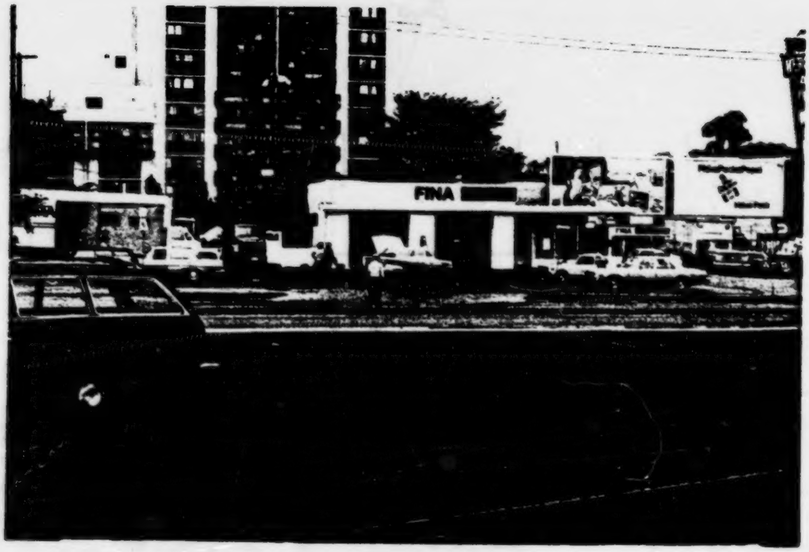


FIGURE 3-10: View of Johns Street Site

FIGURE 3-11: View of Oak Avenue Site

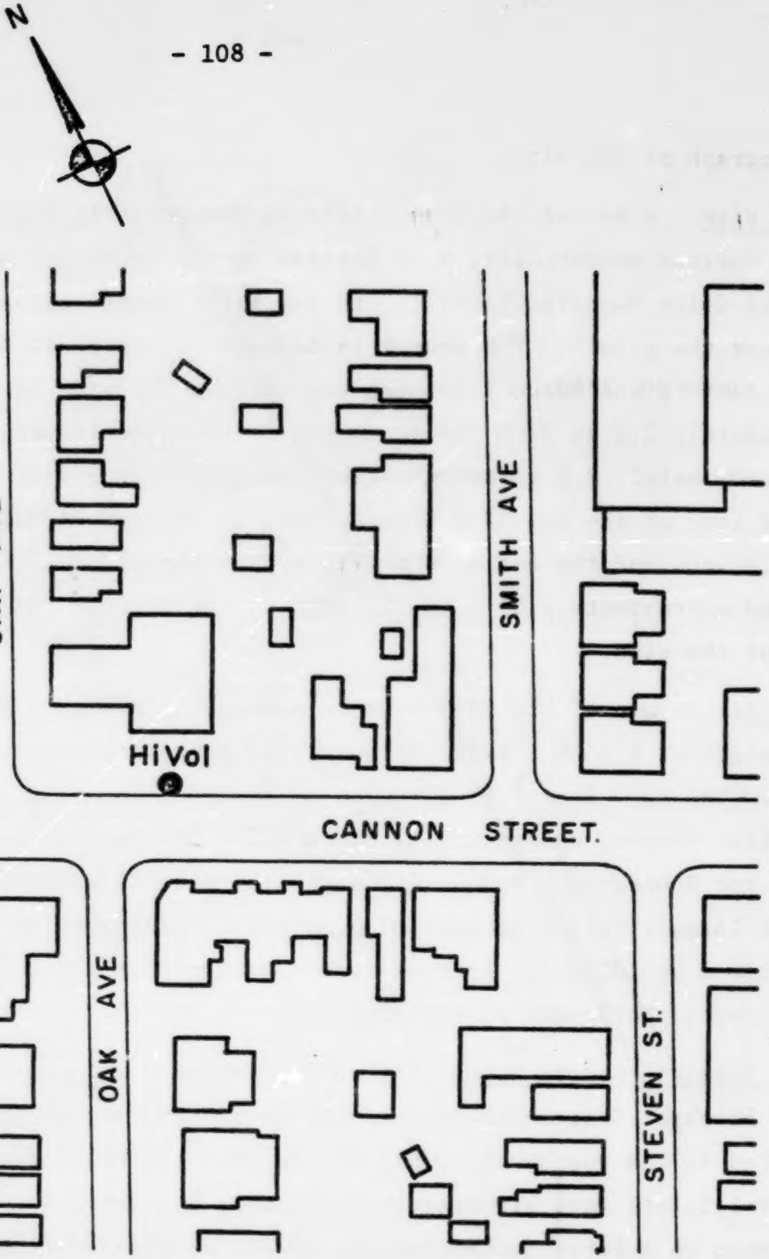

N
OAK AVE
SMITH AVE
Hi Vol
CANNON STREET.
OAK AVE
STEVEN ST.

FIGURE 3-12 OAK AVENUE SITE

a photograph of the site.

School Site. A map of the School site is presented in Figure 3-13. Two HiVols, set to operate sequentially, were located on the northwest corner of the roof of the Bell Cairn Memorial School, with the HiVol inlets being located approximately 7 m above the ground. The school is located in the Beach Boulevard area just north of the ramp to the Queen Elizabeth Way (QEW). The site is in a residential area approximately 1.5 km from the south end of Beach Boulevard, 350 m east of the QEW, and approximately 2.0 km northeast of the heavy industrial area. A small gravel parking lot, at the end of Sierra Avenue, is located directly below the HiVol installations and the beach, which is approximately 50 m wide at this point, is situated approximately 20 m to the west of the school. Figure 3-14 shows a photograph of the site.

Farm Site. A map of the Farm site is presented in Figure 3-16. The HiVol was mounted at a height of 4 m on a hydro pole located approximately 100 m west of West Fifth Street. The farm itself is situated on Hamilton Mountain, on the west side of West Fifth Street, approximately 300 m south of the intersection of West Fifth Street and Stonechurch Road. Althought the area is agricultural, the surrounding land is largely fallow because of proposed developments in the area. A tilled area, 150 m by 100 m was located approximately 75 m north of the site. Figure 3-15 shows a photograph of the site.

Stelco Research Centre Site. Figure 3-17 shows a map of the area surrounding the Stelco Research Centre (SRC) site. Three HiVols, set to operate sequentially, were installed at the southwest corner of the roof of the Stelco Research Centre (SRC). The HiVol inlets were situated approximately 8 m above the ground. The building is located on a large (approximately 30 acres) grassed lot, with paved parking lots on the northwest side. A small housing development is situated to the southwest, and approximately 500 m to the south is the intersection of Highway 403 and the QEW, two heavily travelled freeways (combined ADT is approximately 10,000). The heavy industrial area of Hamilton is situated approximately 8 km to the south of this site.

Figure 3-18 is a photograph of the site and shows a view of the HiVols looking southeast from the roof of the Research Centre building.

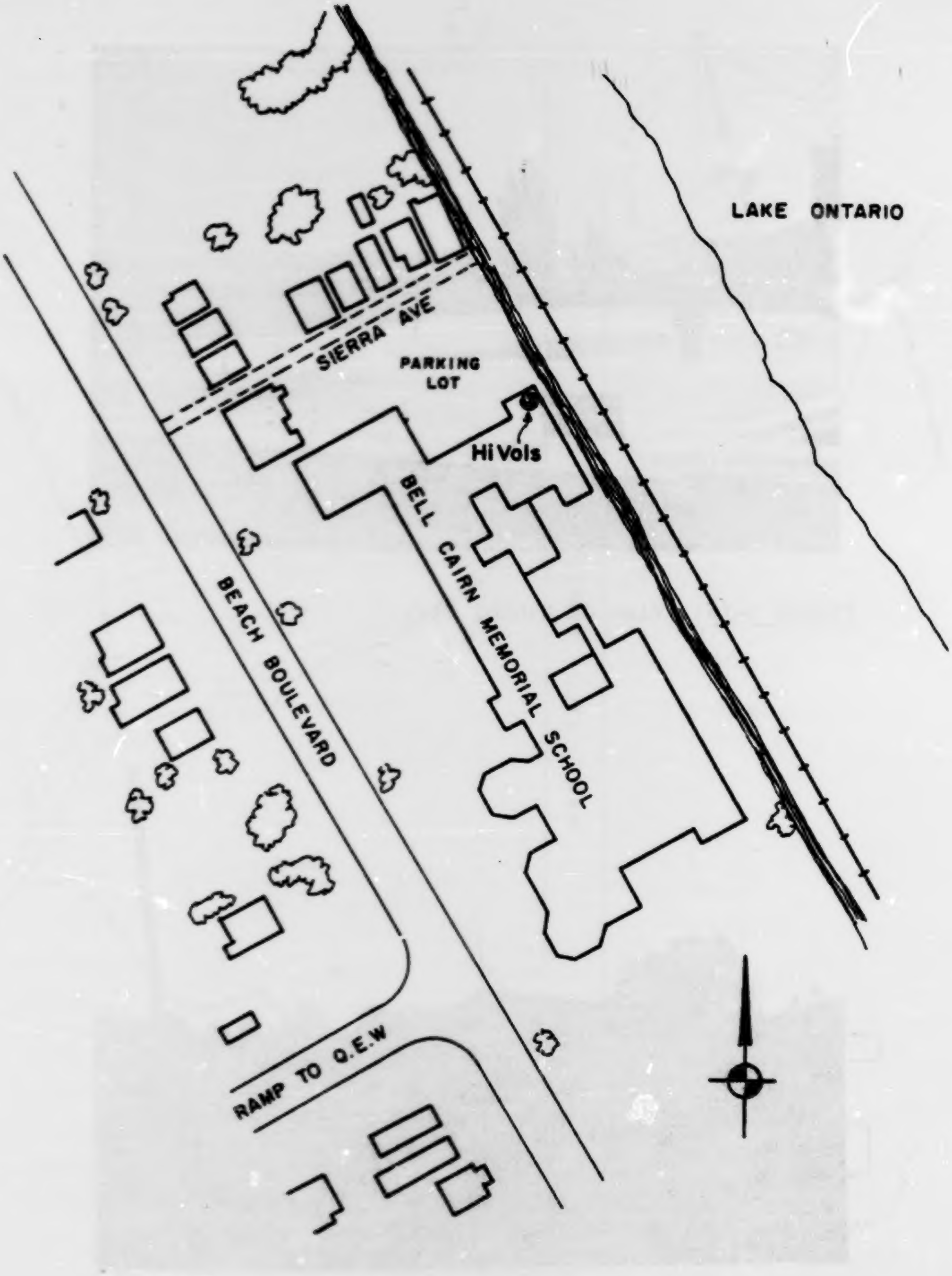

LAKE ONTARIO
SIERRA AVE
PARKING LOT
Hi Vols
BELL CAIRN MEMORIAL SCHOOL
BEACH BOULEVARD
RAMP TO Q.E.W

FIGURE 3-13 SCHOOL SITE

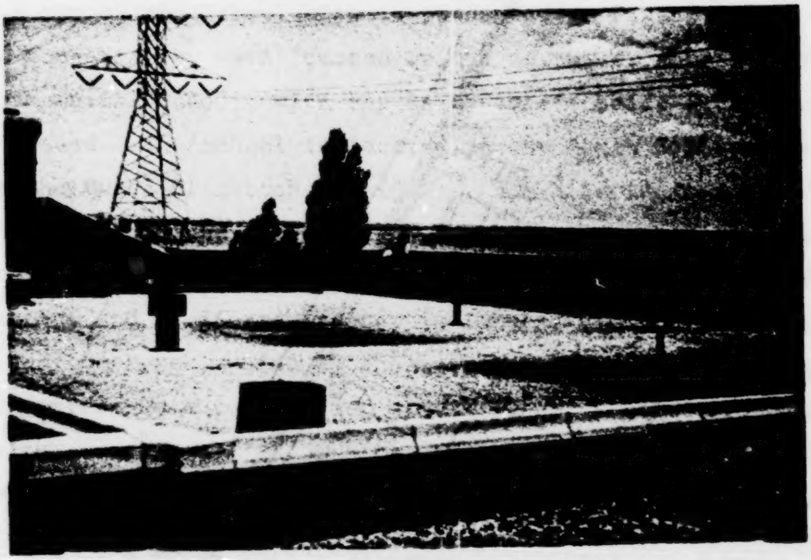


FIGURE 3-14: View of School Site

FIGURE 3-15: View of Farm Site

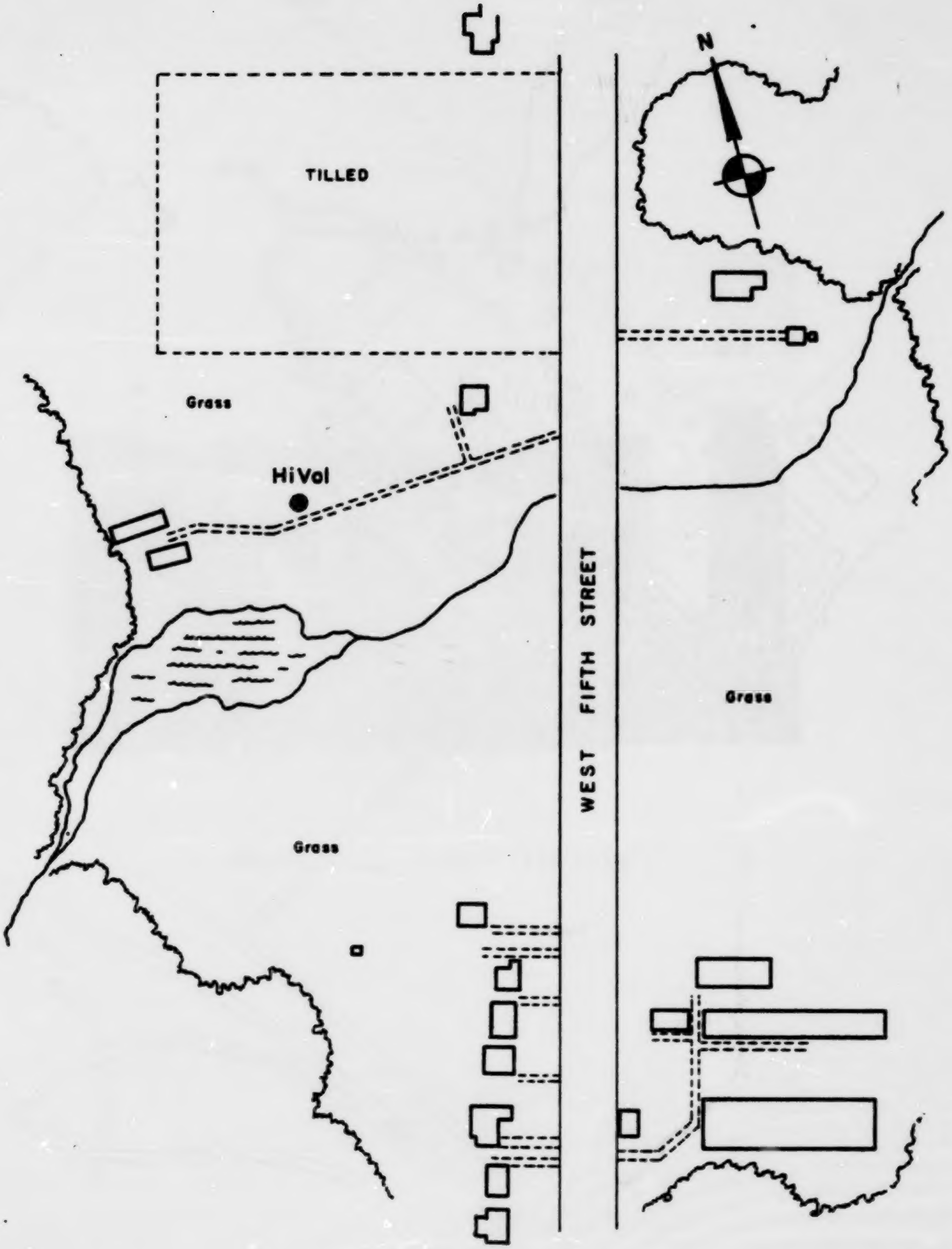

N
TILLED
Grass
HiVol
WEST FIFTH STREET
Grass
Grass

FIGURE 3-16 FARM SITE

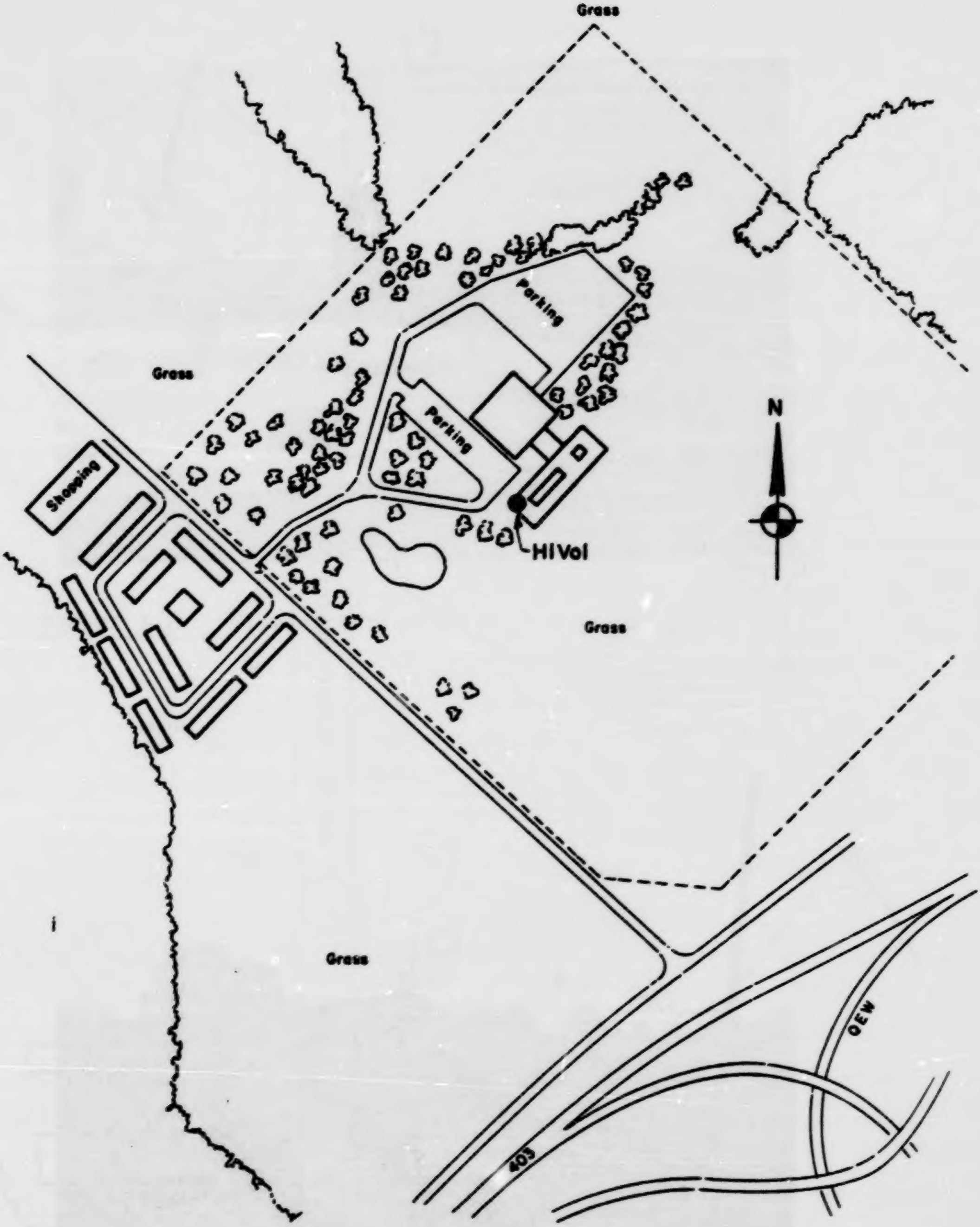

Grass
Grass
Parking
Parking
Shopping
HIVol
N
Grass
Grass
QEW
403

FIGURE 3-17 MAP OF STELCO RESEARCH CENTRE SITE

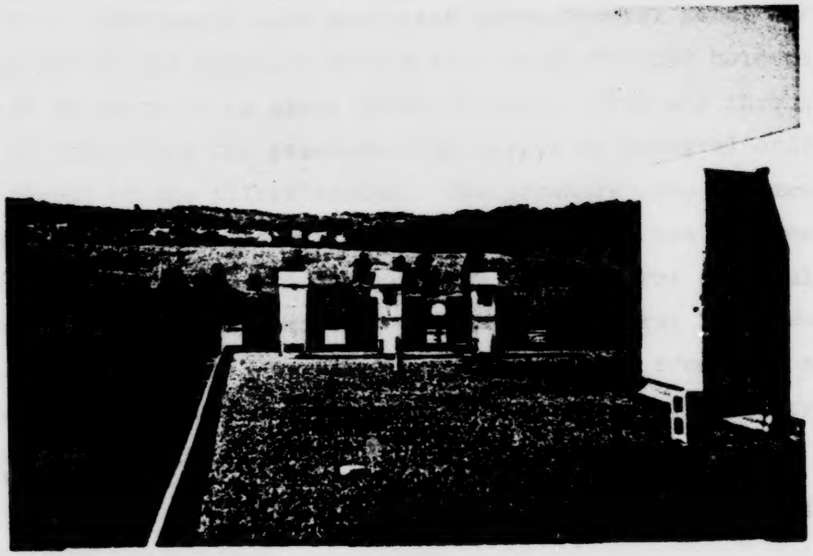


FIGURE 3-18: **View of SRC Site**

FIGURE [illegible]
[illegible]

3.4 Particulate Characterization

Two kinds of particulate measuring techniques were used. The first of these was the determination of TSP levels using HiVols, and the second was the assessment of specific size fractions using dichotomous samplers.

3.4.1 TSP Measurements

TSP levels were monitored using General Metal Works Model GMWL-2000 high-volume air samplers fitted with Model FH-2100 holders and using Gelman type A/E 20 cm by 25 cm glass fibre filters. Flowrate through the filter was measured by monitoring the pressure drop across an integral orifice meter located in the throat of the filter holder. The pressure drop was measured by manometer readings taken across the orifice meter. Flowrate was obtained from a calibration curve of flowrate versus orifice pressure drop for the particular instrument. Each instrument was calibrated prior to use using a General Metal Works Model GMW-25 HiVol calibration kit. As HiVol motors burnt out from time to time during the study, each replacement motor was also calibrated prior to installation in the field. A typical calibration curve is illustrated in Figure 3-19.

In subsequent discussions, each HiVol location will be uniquely described using the following convention:

- For the Experimental site:

  Experimental 1 (E1) is the HiVol located on Tower 1 (3 m from the road) at the 15 m level, Experimental 2 (E2) is the HiVol located on Tower 1 at the 8 m level, and Experimental 3 (E3) is the HiVol located on Tower 1 at the 4 m level. Experimental 4 (E4) and Experimental 5 (E5) are the HiVols located on Tower 2 (33.5 m from the road edge) at the 4 m level, and Experimental 6 (E6) is the HiVol located on Tower 3 (61 m from the road edge) at the 4 m level. Experimental 7 (E7) is the HiVol located on the roof of the trailer. The arrangement is illustrated schematically in Figure 3-20a.

- For the Control site, Control 1 (C1) is the HiVol located on the tower at the 15 m level, Control 2 (C2) is at the 8 m level, and Control 3 (C3) is at the 4 m level. The arrangement is illustrated schematically in Figure 3-20b.

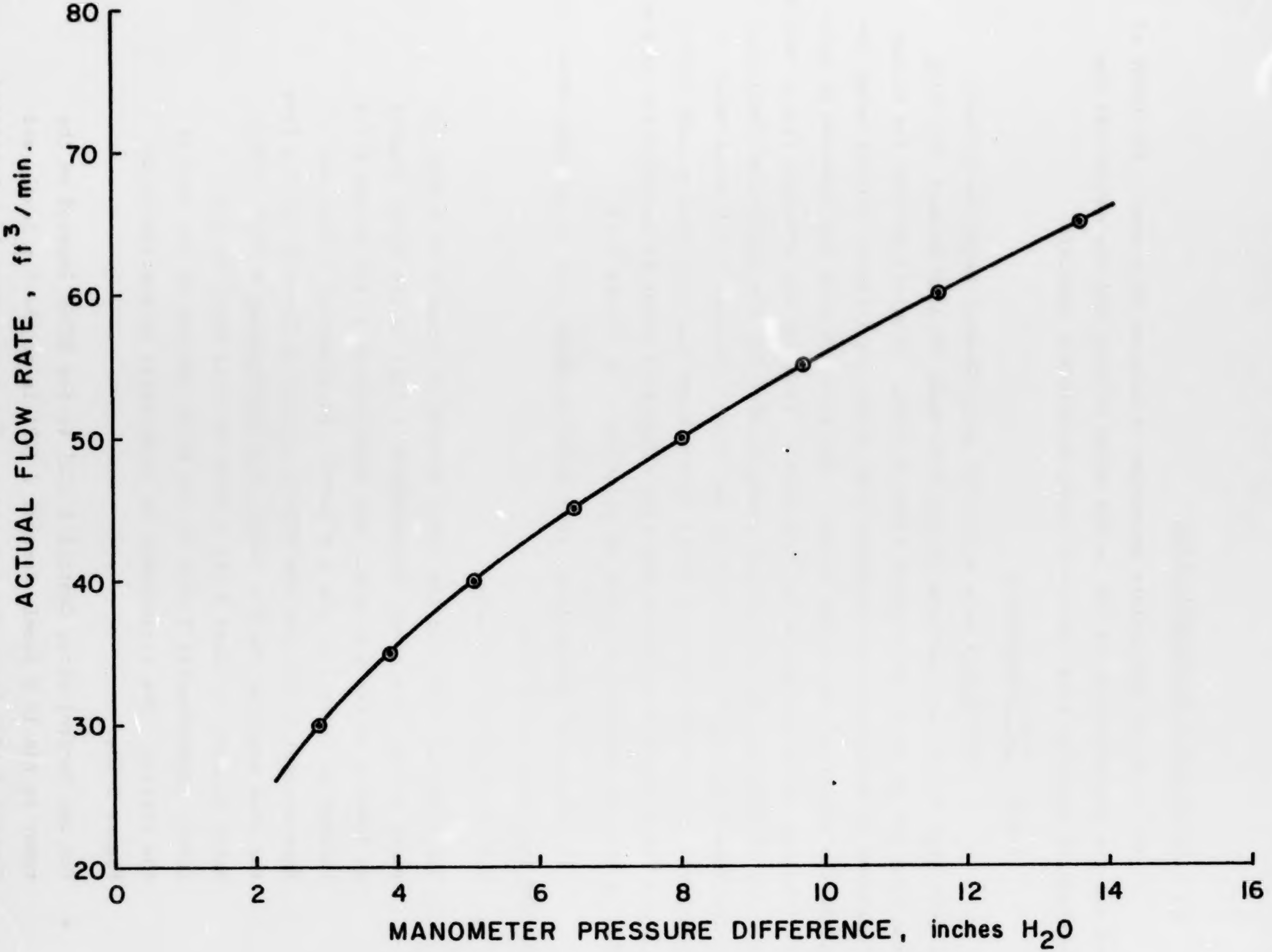
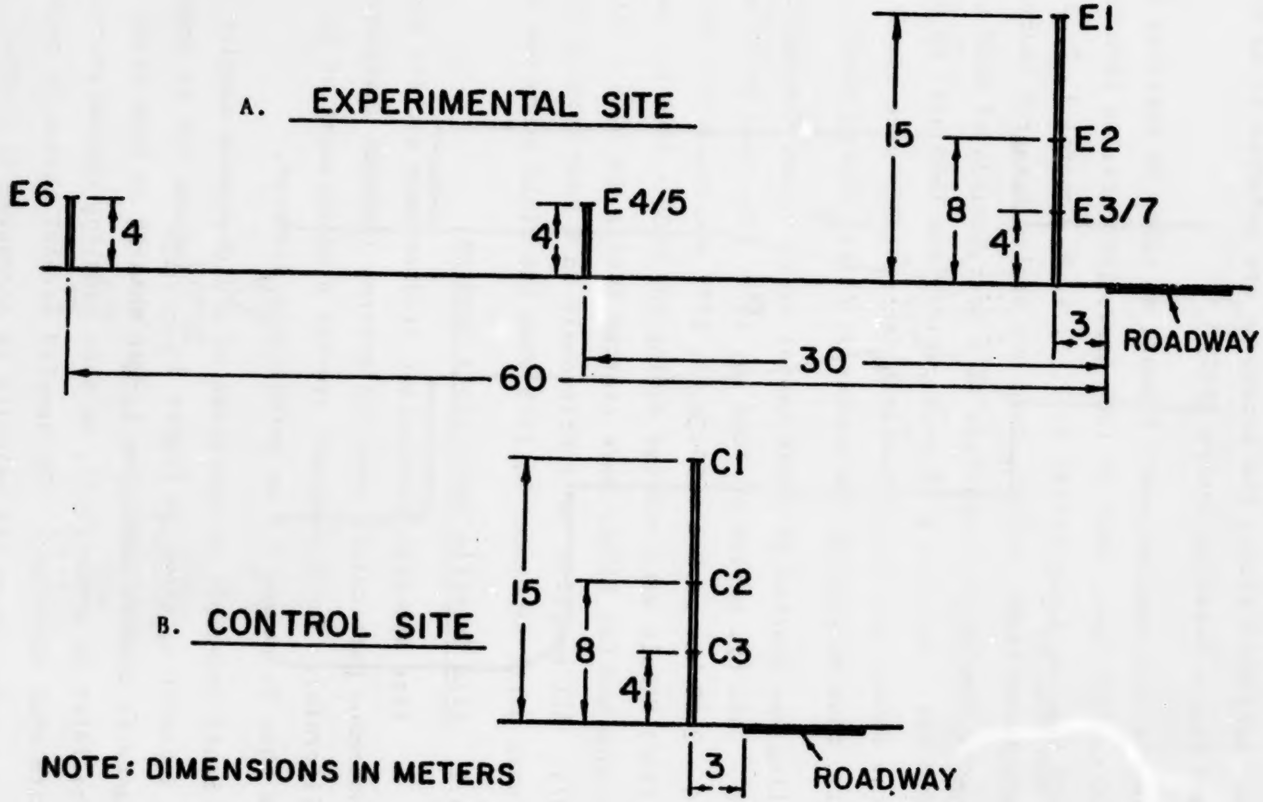


FIGURE 3-19 TYPICAL HiVol CALIBRATION CURVE


A. EXPERIMENTAL SITE
E1
E2
E3/7
E4/5
E6
15
8
4
4
4
3
30
60
ROADWAY
B. CONTROL SITE
C1
C2
C3
15
8
4
3
ROADWAY

NOTE: DIMENSIONS IN METERS

FIGURE 3-20 SCHEMATIC OF SAMPLER LAYOUT.

A - EXPERIMENTAL SITE
B - CONTROL SITE

- For the John Street and Oak Avenue sites, the HiVols are simply referred to as John and Oak.
- For the background sites, the locations are referred to as School, Farm and Stelco Research Centre (SRC).

TSP levels were sampled every 6 hours as close as possible to a schedule of 0000 to 0600 hrs., 0600 to 1200 hrs., 1200 hrs. to 1800 hrs., and 1800 hrs. to 2400 hrs. at Experimental 1, 2, 3, 4, 6, Control 1, 2, 3, John and Oak. At the background sites, School, Farm and Stelco Research Centre (SRC), the TSP levels were sampled on a schedule of 6 hour periods of 0600 to 1200 hrs., 1200 hrs. to 1800 hrs., and then a 12 hour period from 1800 hrs. to 0600 hrs. The HiVols at the School and Stelco Research Centre (SRC) were set on timers to run sequentially, thus minimizing the number of filter change visits required.

Sampling was started at Experimental 1, 2, 3, and Control 1, 2 and 3 during the 1800 - 2400 hr. period on June 10, 1979. The Farm HiVol was started during the 1800 - 2400 hr. period on June 14, 1979 and the School and Stelco Research Centre (SRC) HiVols were started during the 1800 - 2400 hr. period on June 15, 1979. The John and Oak HiVols were started during the 0000 - 0600 hrs. period on June 16, 1979. All sampling ran continuously in 6 hour periods for 24 hours a day, 7 days a week until September 7, 1979 when the field study was ended.

3.4.2 Size Specific Particulate Studies

Size specific particulate studies were carried out using Beckman automated dichotomous particulate sampling systems (Beckman Instruments Inc., Fullerton, California). These samplers provide a measurement of the fraction of particles less than 15 μm and 2.5 μm aerodynamic diameter.

The basic principle of operation of a dichotomous sampler using a single-stage virtual impactor is shown in Figure 3-21. Ambient air is drawn in through an inlet designed to prevent particles larger than 15 μm from being sampled. The geometry of the inlet is symmetrical, so that sampling characteristics do not change appreciably with wind direction. The sampled aerosol stream is then passed through an acceleration nozzle, where its velocity is increased to a speed, V_j. Concentric with the flow axis and a short distance below the discharge plane of the acceleratio nozzle is a collection nozzle. Larger particles that have been accelerated in the upper nozzle are driven by inertia into the collection nozzle. Only a small portion

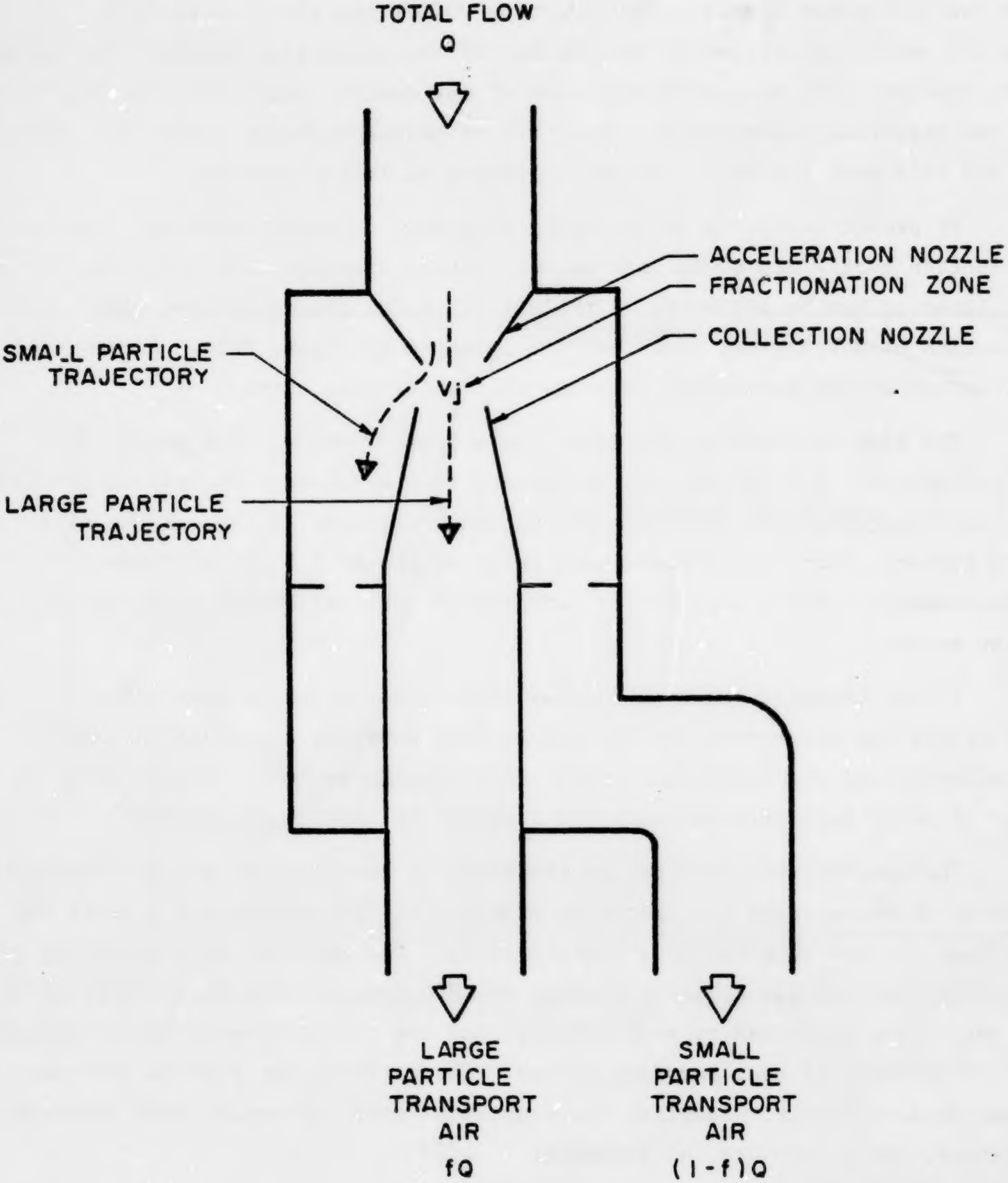

TOTAL FLOW
Q
ACCELERATION NOZZLE
FRACTIONATION ZONE
COLLECTION NOZZLE
SMALL PARTICLE TRAJECTORY
V_j
LARGE PARTICLE TRAJECTORY
LARGE PARTICLE TRANSPORT AIR
fQ
SMALL PARTICLE TRANSPORT AIR
(1-f)Q

FIGURE 3-21 VIRTUAL IMPACTOR FOR DICHOTOMOUS SAMPLING.

(about 10% of the total flow Q, which enters the acceleration nozzle) is drawn through the collection nozzle. The remaining 90% of the air flow (1-F) Q, carries the smaller particles to the outside of the collection nozzle. The large particle fraction will always contain some of the smaller particles, the fraction f, and the resulting concentration data must be correspondingly corrected. The coarse and fine particle fractions are collected on Teflon filters.

By proper selection of the total flowrate, flowrate fractions, acceleratio and collection nozzle diameters, and between nozzle spacings, the cut-point of the virtual impactor can be adjusted. A typical curve for the collection efficiency as a function of aerodynamic particle size is shown in Figure 3-22. A change of total flowrate or the fractional flowrate will shift this curve.

The samplers used in the study had a total (nominal) flowrate of 16.7 litres per minute. 1.7 litres per minute were sampled through the coarse particle filter, with approximately 15 litres per minute being sampled through the fine particle filter. These flows give a cut point of around 2.5 μm aerodynamic particle diameter. The flowrates for each sample were calibrated using Hastings mass flow meters.

Filter changing occurred automatically under microprocessor control. The microprocessor was programmed for the sample time duration and number of samples to be collected and the instrument would automatically sequence through up to 36 samples. A paper tape printout supplied a record of sampler operations.

The samplers were mounted on the roofs of the trailers at the Experimenta and Control sites, placing the inlets at a height of approximately 4 m above the ground (i.e., E3 and C3 locations, respectively). The samplers were installed on June 25, 1979 and the first sample started at 1800 hrs. on that day. Trays of 36 filter pairs were installed to each sampler, and the microprocessor set to change filters after every 12 hour sampling period. The first filter pair in each set of trays was used as blanks. Sampling was continuous every 12 hours, with necessary tray changes, until 1800 hrs. on September 7, 1979.

Total particulate loading on each filter were determined by β-attenuation at the U.S. EPA. This will be described more fully in a subsequent section.

3.5 Road Sweeping Experiment

Two street-cleaning methods were evaluated during the study using

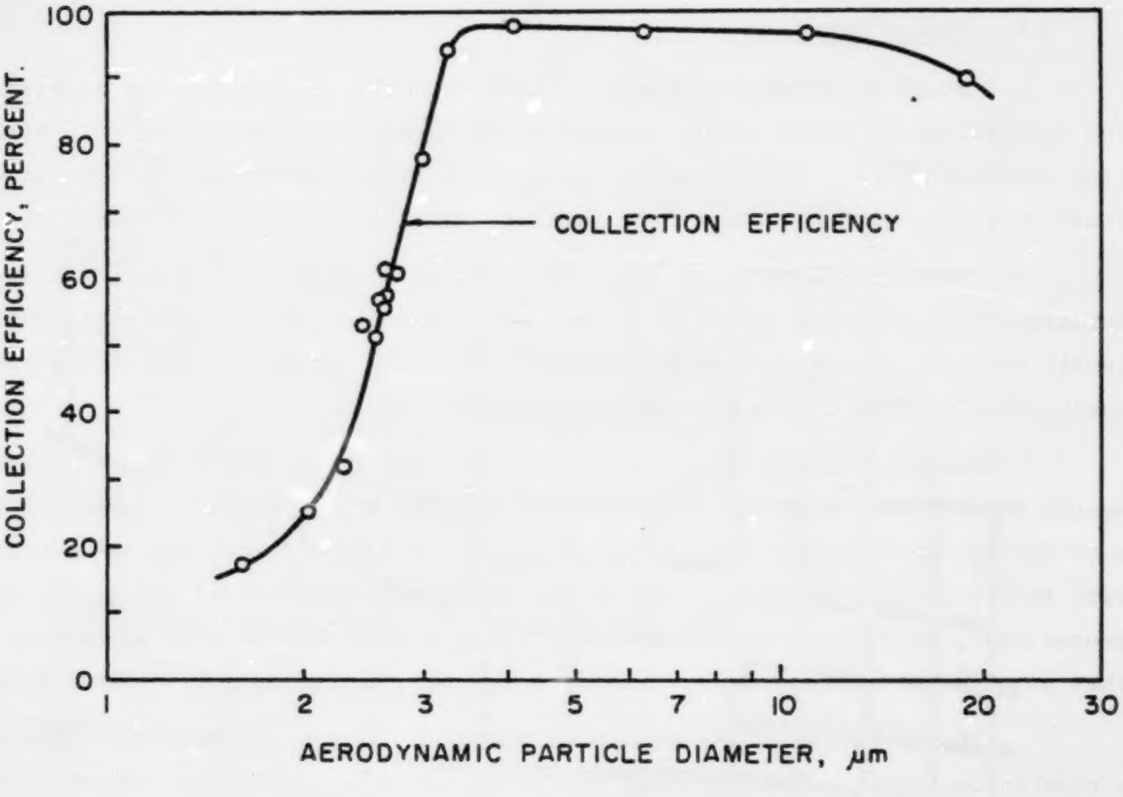


FIGURE 3-22 COLLECTION EFFICIENCY CURVE FOR DICHOTOMOUS SAMPLER.

mechanical and vacuum sweepers of conventional design. The first phase of the study (up to July 7, 1979) was used to gather baseline data during normal street-cleaning activities. From July 8, 1979 to August 7, 1979, mechanical sweeping was carried out in the area surrounding the Experimental site as defined in Figure 3-23. During the night (2300 hrs. to 0700 hrs.) and morning (0700 hrs. to 1500 hrs. shifts (hours worked by Municipal staff) of every day during this period, the area was swept once. From August 8, 1979 to September 9, 1979, the same area was cleane by vacuum sweeper on the same schedule.

3.6 Tracer Experiment

Staff at McMaster University have recently conducted brief studies of the feasibility of using tracer techniques to assess the reentrainment of particles from roadways (226). The intensive particulate measurements made in the current study offered a good opportunity to further assess and apply this concept.

The tracer experiment entailed spraying a solution of a tracer compound, europium chloride, onto the road surface and monitoring the ambient particulate levels adjacent to the road using cellulose filters. These filters were subsequentl analyzed by neutron activation analysis as described below.

The study was carried out at the Experimental site. HiVols at Experimental 5 and 7 were used for sampling with Whatman 41 cellulose filters. Sampling with Whatman 41 filters commenced at 0000 hrs. on July 17, 1979 and was continued with filter changes every 6 hours, as for the glass fibre filter TSP study, until September 7, 1979. Whatman 41 cellulose filters were used in this experiment as they provide low background and interferences for neutron activation analysis.

Thirty litres of a solution of europium chloride ($EuCl_3$) was contained in a plastic container. The container was connected to a gas-driven pump which pumped the $EuCl_3$ solution through five spray nozzles mounted on a boom, attached to the rear of a van. The solution was sprayed onto all four lanes of an approximately 120 m long stretch of Cannon Street in front of the Experimental site. Spraying was only carried out if, from weather forecasts for the day, winds were predicted to blow from south to north across Cannon Street (i.e. the wind would carry tracer laden road dust towards the samplers) and also if no rain was predicted for at least the first 12 hours after spraying. This latter condition was necessary because of the solubility of the $EuCl_3$ tracer. These restrictions resulted in the tracer

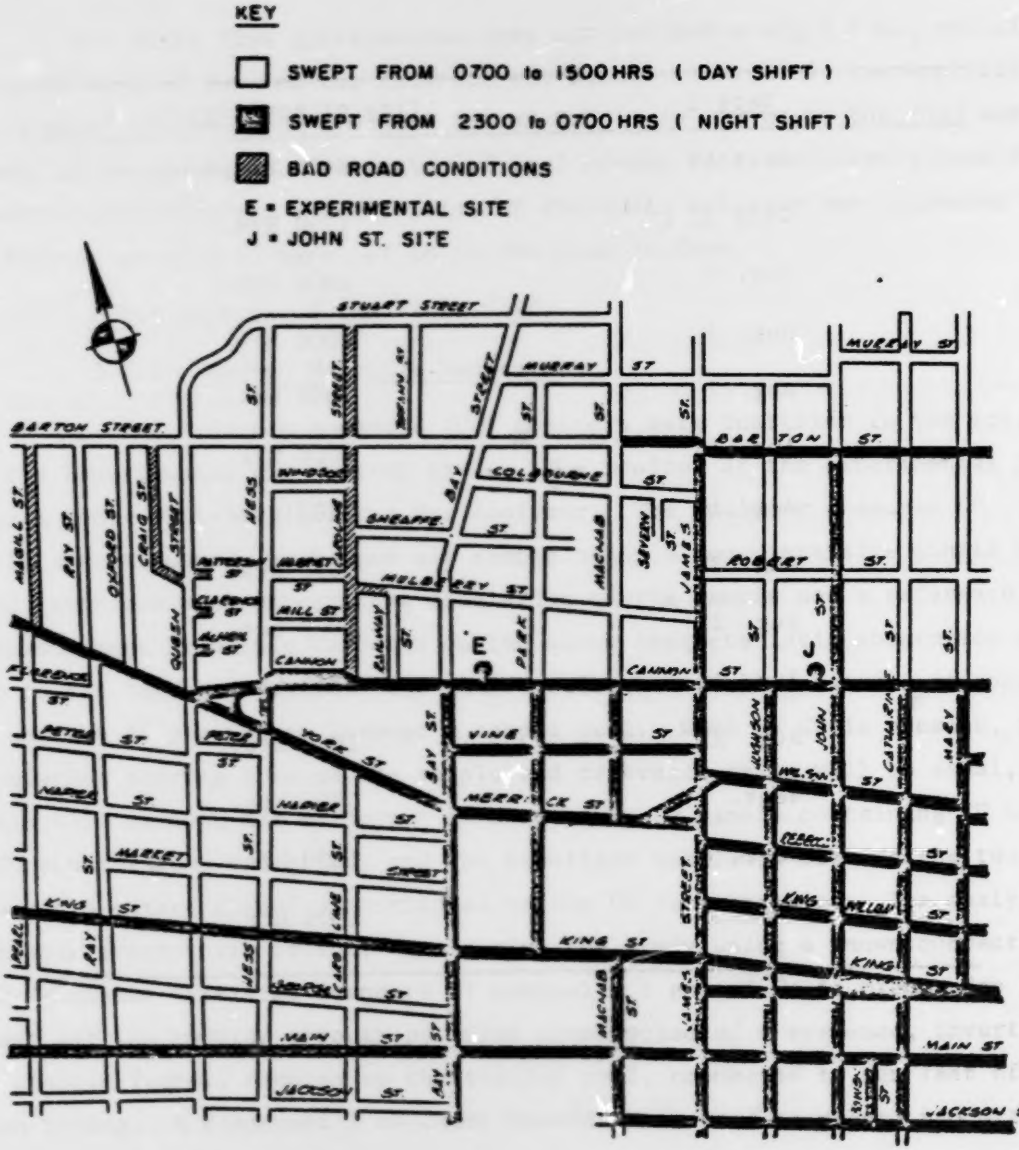

KEY
☐ SWEPT FROM 0700 to 1500HRS (DAY SHIFT)
■ SWEPT FROM 2300 to 0700HRS (NIGHT SHIFT)
▨ BAD ROAD CONDITIONS
E = EXPERIMENTAL SITE
J = JOHN ST. SITE
STUART STREET
BARTON STREET
MURRAY ST
MURRAY ST
BARTON ST
MAGILL ST.
RAY ST.
OXFORD ST.
CRAIG ST.
STREET
HESS
QUEEN
ST.
STREET
BAY STREET
WINDSOR
CAROLINE
SHEAFFE ST
COLBOURNE ST
MULBERRY ST
MILL ST
CANNON
RAILWAY
ST.
PARK
MACNAB
SEVERN ST.
JAMES
ROBERT ST.
E
J
CANNON ST
FLORENCE
ST
PETER ST.
PETER ST
YORK ST
BAY ST.
VINE ST
MERRICK ST
NAPIER ST.
NAPIER ST.
JACKSON
JOHN
CATHARINE
MARY
ST.
ST
ST.
WILSON ST
PERRY ST
MARKET ST.
ST.
ST
STREET
KING ST
KING ST
KING ST
KING ST
PEARL
RAY
HESS
CAROLINE
JAMES
MACNAB ST
MAIN ST
MAIN ST
JOHN ST
JACKSON ST.
JACKSON ST
BAY

FIGURE 3-23 . AREA CLEANED DURING SWEEPING EXPERIMENT.

TABLE 3-3

Tracer Applications

Date	Time of Application
July 19	0430 hrs.
July 31	1100 hrs.
Aug. 1	1000 hrs.
Aug. 3	1000 hrs.
Aug. 7	1000 hrs.
Aug. 16	1000 hrs.
Aug. 19	1000 hrs.
Aug. 20	1030 hrs.
Aug. 25	1000 hrs.
Aug. 26	1000 hrs.
Aug. 27	1000 hrs.
Sept. 1	0900 hrs.
Sept. 4	1000 hrs.
Sept. 5	1000 hrs.

experiment being carried out on 14 occasions between July 17, 1979 and September 7, 1979. These applications are listed in Table 3-3. As can be seen from Table 3-3, apart from the first application, all applications were carried out in mid-morning (0900 to 1100 hrs.) and took approximately one-half hour to complete.

The first five applications were carried out using a $EuCl_3$ solution containing 55 mg/L of Eu. At the flowrate and nozzle sizes used, the application rate was 9.5 ml/m^2 resulting in a deposition of 0.53 mg/m^2 of Eu on the road surface. However, after subsequent evaluation of preliminary data indicated a need for increased sensitivity, the concentration of the $EuCl_3$ solution was increased resulting in a deposition of 2.03 mg/m^2 of Eu to the road surface.

3.7 Other Aspects of the Field Study

3.7.1 Carbon Monoxide Monitors

Carbon monoxide (CO) monitors were installed in the trailers at both the Experimental and Control Sites. The monitor at the Experimental Site was a Bendix Model 8501-5CA Infrared Gas Analyzer. The analyzer measures CO concentration in a continuously exchanged air sample using a non-dispersive single beam infrared technique with alternating modulation of the sample and a reference cell. The measurement principle is based on the known characteristic absorption spectrum of CO in the infrared region. The sealed reference cell contains a nonabsorbing gas, and the sample passes through a sample cell. When no CO is present, the amounts of radiation passing through the sample and reference cells will be equal, the signals will cancel, and no output is seen. When a sample containing CO is analyzed, the CO absorbs some radiation, and the resultant imbalance between the two cells produces an output signal proportional to the CO concentration. The analyzer was calibrated every three to four days during the study using a known concentration of CO (Matheson Certified Standard of nominally 1 ppm of Co in clean, dry air). Ambient air was sampled through an inlet constructed of a screened, inverted eight inch plastic funnel, mounted on the trailer roof, connected to ten feet of 4 mm ID teflon tubing. A Rikadenki 1 mV chart recorder was used to record proportional output signals from the analyzer.

The CO monitor at the Control site was a Hartmann and Braun Uras 2 Infrared Gas Analyzer. The principle of operation, calibration procedures and sample collection and recording are as for the Bendix instrument above.

3.7.2 Coefficient of Haze (COH) Monitoring

COH was monitored at both the Experimental and Control sites using RAC Model F filter paper tape monitors. These monitors use the sampling principle of drawing a known amount of ambient air into an inlet tube, passing the air thorugh a nozzle containing a section of the filter paper tape and through a pump to exhaust. Flow was set on both monitors to sample air at a rate of 7 L/min. Air was sampled through the filter tape for a preset time, after which the tape is automatically sequenced to the next sampling position. The monitors were initially set to sample at 1-hour intervals starting on June 13, 1979, but were reset to sample at 2-hour intervals on July 4, 1979. The monitors were reset because the 1-hour sample interval was found to be too short to obtain reliable COH data at the relatively low levels prevailing during the study period.

The particulate loading was measured by light transmittance, with the instrument being zeroed before each reading in the unexposed tape are between the exposed spots on the tape. The amount of reduction in light transmittance caused by the particulate loading on the filter paper was converted to unit of COH by the equation:

$$\text{COH/1000 linear feet} = \frac{\text{OD} \times 100}{\text{L}}$$

$$\text{Where OD, optical density} = \log\left(\frac{100}{\%\text{T}}\right)$$

$$\text{T} = \text{Transmittance}$$

$$\text{L} = \frac{\text{flow (ft.}^3\text{/min)} \times \text{sampling time (min)}}{1000 \times \text{spot area (ft.}^2\text{)}}$$

The tapes were 100 ft. spools of 1-1/4 in. wide strips of Whatman 4 filter paper. The tape monitors were run continuously until 1800 hrs. on September 6, 1979.

3.7.3 Dustfall

Dustfall jars were installed at the Experimental and Control sites. Dustfall jars are open-top collectros, 6 in. in diameter and 12 in. deep, used to sample settleable particulate matter. The jar at the Experimental site was mounted on a bracket at a height of 4 m attached to the meteorological tower, which was itself attached to the trailer. The jar at the Control Site was mounted on a hydro pole, at a height of 4 m, located approximately 5 m east of the HiVol tower, adjacent to the road.

Dustfall was collected from July 10, 1979 to August 10, 1979 and from August 10, 1979 to September 6, 1979. These periods approximately coincide with the two sweeping periods.

3.7.4 Surface Road Dust Sampling

Samples of dust from the surface of the road were collected at four Cannon Street sites. These were collected to obtain information on total dust loadings on the road surface, and also to determine levels of resuspendable dust.

Samples were obtained by blocking off a 20 m section of Cannon Street in front of the sampler at a particular site. For the Environmental and Control sites, sampling was carried out in front of the HiVol towers. Sampling was effected using a Speedivac Model 309 industrial vacuum cleaner. The samples were collected in paper bags inside the vacuum cleaner. Fine material which passed through the paper was collected by a cloth filter on the inlet to the vacuum cleaner motor. This material was transferred to plastic sample bags by brushing the cloth filter with a fine camel's hair brush. After collection, the paper sample bags were stored in plastic bags. Two samples were collected during each vacuuming, one for each half of the road. A schedule of sampling at the four Cannon Street sites (Experimental, Control, John and Oak) is presented in Table 3-4. The schedule was designed to provide at least two samples at each site during the mechanical and vacuum sweeping periods.

Each sample was sieved to determine the fraction of resuspendable dust, which is defined as that containing particulate matter of less than 37 μm diameter. This fraction was determined by weighing the total sample and then sieving the samples through a 400 mesh (37 μm) sieve and weighing the less than 400 mesh portion. Most of the larger particles in the samples were removed by preliminary sieving through a 20 mesh sieve. The samples were sieved using an automatic shaker on a 5-minute cycle. This short time period was used to minimize mechanical fracture of the dust particles during the sieving operation, as recommended by earlier workers.

TABLE 3-4

Schedule of Surface Road Dust Sampling

Site	Sample Date
Experimental	July 4
	July 17
	Aug. 20
	Sept. 6
Control	July 5
	July 18
	Aug. 8
	Aug. 27
	Sept. 6
John St.	July 7
	July 25
	Aug. 23
	Sept. 5
Oak Ave.	July 6
	July 23
	Aug. 22
	Sept. 7

3.8 Analytical Methods and Procedures

3.8.1 Filter Preparation and Weighing

All glass fibre filters used in the HiVol sampling network were conditioned and weighed before and after exposure. All filter preparation was carried out in a room in which the relative humidity was controlled at 50 ± 5%. This was accomplished by keeping an air-conditioned room closed to the outside, except for necessary entrances and exists, and using a dehumidifier to augment the air conditioning. Relative humidity was monitored using a wet and dry bulb thermometer hygrometer.

During all handling procedures, plastic gloves were worn and tweezers used. Filters were handled in batches of 100. The filters were stamped with an identification number and then placed in a conditioning cabinet. This was a specially constructed cabinet with slots to accommodate the filters, and sliding doors to keep room air from circulating through the cabinet, minimizing dust settlement. The cabinet was kept at 50% relative humidity using a saturated solution of magnesium nitrate (solubility 125 g/100 cm^3, constant humidity 52% at 24.5^o). The filters were well spaced within the cabinet to allow good circulation of the conditioning atmosphere. The filters were left in the cabinet for a minimum of 24 hours.

After conditioning, the filters were removed from the cabinet and weighed to the nearest mg on an analytical balance specially modified to accommodate the width of the HiVol filter (25 cm) without having to bend or fold the filter. ID number and weight for each filter was recorded in a log book. The weighed filters were then placed sequentially in boxes for shipment to the field. Pre-stamped envelopes were also prepared for storage of the filters after exposure.

In the field, filters were again handled with gloves and tweezers. The filters were loaded into cassettes, with the filter number and its HiVol location recorded in a log book. The cassette was loaded into a HiVol unit and exposed for a nominal 6-hour period with the actual "on" and "off" times of exposure, HiVol number and location, pressure drop on and off, date and operators' names being recorded on the envelope. The exposed filters were returned to the laboratory.

In the laboratory, the exposed filters were removed from the envelopes, placed still folded in the conditioning cabinet, and allowed to come to constant humidity over at least a 24-hour period. Extremely wet filters, however, required several days to reach equilibrium. The filters were reweighed to the nearest mg and then returned to their envelopes for storage. All relevant information was recorded in the log book and on each filter envelope.

TSP concentration was calculated using the equation:

$$TSP = \frac{(W_f - W_i) \times 10^6}{V}$$

where,

TSP is in $\mu g/m^3$

W_f is the final weight

W_i is the initial weight

and $V = \frac{(Q_i + Q_f)\ t}{2}$ = total volume sampled, m^3

Q_i = initial HiVol flow, m^3/min

Q_f = final HiVol flow, m^3/min

t = sampling time, min

10^6 converts g to μg

Each filter was stored chronologicall according to site and HiVol in case further analysis of the filter was proscribed.

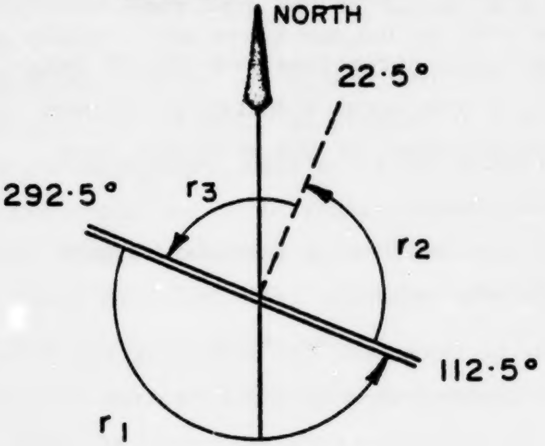
3.8.2 Filter Selection for Analysis

A sample of filters was selected from the total set of exposed filters to be analyzed for various elements and compounds. The selection of this filter sample was made on the basis of meteorological regimes, with primary emphasis given to wind direction (r), wind speed (u), and precipitation events (p). This method of selection assured an adequate representation of all meteorological regimes of interest. The criteria are illustrated in Figure 3-24 and can be summarized as follows:

(1) Wind Direction - this is a very important criterion in distinguishing the effect of road dust from that of other particulate sources, especially industria emissions. Thus, the wind rose was divided into three sectors:

- r_1. This sector included all wind directions from south of

WIND DIRECTION



r_1 = WINDS ACROSS CANNON ST FROM 112·5° TO 292·5°

r_3 = WINDS FROM NORTH-WEST

r_2 = WINDS FROM NORTH-EAST – INDUSTRIAL AREA

WIND SPEED

u_1 = WINDS LESS THAN 8 km/hr (5 mph)

u_2 = WINDS FROM 9-18 km/hr (5-12 mph)

u_3 = WINDS GREATER THAN 18 km/hr (12 mph)

PRECIPITATION

P_1 = PRECIPITATION OCCURRED

P_2 = NO PRECIPITATION OCCURRED

FIGURE 3-24 SUMMARY OF SELECTION CRITERIA FOR FILTERS FOR ANALYSIS

Cannon Street including winds that blew along the street in both directions. Cannon Street runs approximately WNW-ESE, and thus r_1 encompassed this semicircular sector of the wind rose.

- r_2. This sector included all wind directions from the NE part of Hamilton, where almost all of the heavy industry is concentrated. This sector included that part of the wind rose from NNE-ESE.
- r_3. This sector included all winds blowing from the NW part of Hamilton (i.e., the WNW-NNE sector).

(2) Wind Speed - this criterion is important for assessing the effects of reentrainment and transport of particulates into the Hamilton area. Three wind speed criteria were considered:

- u_1 included wind speeds from 0-9 kph; at very low wind speeds, the effect of dust reentrainment caused by vehicle movement can be expected to predominate and prolong periods of stagnation and can result in high TSP loadings. Particulates transported into the region and transport of industrial emissions should be at a minimum during these periods.
- u_2 included wind speeds from 9-18 kph. It has been demonstrated that dust reentrainment by winds becomes important at speeds above approximately 18 kph.
- u_3 included wind speeds greater than 18 km/hr. Fugitive dust reentrainment has been shown to become significant at this point.

(3) Precipitation Events - the effect of precipitation is to suppress TSP levels. This is because of washout effects as well as the wetting of dust on road surfaces, etc. which suppresses reentrainment effects. This criterion was divided according to wet/dry periods; and any measurable precipitation (> 1 mm) constitute a wet period.

- P_1: Precipitation during the sampling periods
- P_2: No precipitation during the sampling periods

Wind data from MOE Woodward Street and precipitation data from the Royal Botanical Gardens were used in assigning sampling periods to the regimes.

3.8.3 Chemical Analysis

Ion Chromatography. For anion determination a 1" x 9" strip was cut from the exposed filter. The strip was cut up into small pieces and placed into a 250 mL conical flask. 50 cm^3 of eluant solution was added, the flask stoppered and shaken mechanically for 30 min. An aliquot of the extracted solution was injected into the ion chromatograph using a 0.1 cm^3 sample loop. The eluant solution was 1M in sodium carbonate and 1M in sodium bicarbonate. Anions determined were fluoride, chloride, bromide, phosphate, nitrate, nitrite, sulphate and sulphite. However, it was found that fluoride, chloride, nitrate, sulphate and in some cases, bromide, were the only anions detected.

In the case of cation determination the above procedure was followed except that the ions were extracted into 50 mL of deionized water and the eluent solution was 0.075 M nitric acid. Cations determined were sodium, potassium and ammonium ions.

Atomic Absorption Analysis. Two sample sizes were used for AA analysis. One procedure used 1 or 2 circles cut from the filter where one circle yields a sample area of 1.767 sq. ins. The other procedure used a 1" x 9" strip cut from the exposed filter. However, the extraction procedures were similar and are described below. For all metals determined, the filter sample was digested 3 times with a 50% solution of aqua regia (a 3:1 mixture of hydrochloric and nitric acids) with prolonged refluxing and taking to incipient dryness between each treatment. This was found necessary in order to solubilize any refractory iron compounds present in the sample. Residues were taken up in a 4% solution of aqua regia and filtered. Filtrate and washings were made up to a fixed volume for analysis by AA. Metals analyzed were:

- For glass-fibre filters: Iron (Fe), Manganese (Mn), Copper (Cu), Zinc (Zn), Lead (Pb) and Chromium (Cr).
- For Whatman 41 cellulose filters: the above metals plus Calcium (Ca), Magnesium (Mg), Aluminum (Al) and Nickel (Ni).

3.8.4 Morphological Analysis

A subset of 16 glass-fibre filters were selected for detailed morphological analysis. These filters were chosen as follows: the sites Farm, Experimental 3, Control 3, and School form an approximate line on a SW-NE axis through the study area. Thus, a set of filters from these four sites were selected for two periods when winds were blowing out of the southwest, one period near the beginning of the study, and one period near the end of the study. A similar selection was made for winds from the northeast. These filters were then analyzed microscopically.

The technique used was to take an approximately 2 cm square sample from the centre third of each filter, put the sample into a stainless steel envelope, place the envelope in a beaker of ethanol and to put the beaker in an ultrasonic bath for 1-2 minutes. The envelope was used to minimize fragmentation of the filter material. The envelope was removed, and the ethanol suspension was filtered through a 47 mm diamter Millipore 0.8 μm type AA filter. A 1 cm^2 portion of this filter was cut out and placed on a microscope slide. Immersion oil with the same refractive index as the Millipore filter material was used to render it transparent during examination. The particulate material was examined in transmitted, polarized light using a Zeiss Universal Light Microscope. The particles were identified and then sized using a Porton graticule in one of the eyepieces for up to 10 fields of view per sample, sufficient for generating a reliable particle size distribution graph. A computer program was then used to determine the volume percent distribution of each type of particle identified in the sample.

In addition to this morpholoigcal analysis, the filters were analyzed by IC for F^-, Cl^-, Br^-, SO_4^{2-}, NO_3^-, NH_4^+, Na^+ and K^+ and by AA for Fe, Zn, Mn, Cu, Pb and Cr.

3.8.5 Neutron Activation Analysis

The samples collected on Whatman 41 filters for 24 hours after each tracer application were analyzed by neutron activation analysis (NAA). In this procedure, a maximum of 24 samples of air filters, including blanks, were irradiated together with eight multielemental standards (four each for As, Co, Cr, Cu, Fe, Mn, Ni, Sb, Se, Zn and another four each for La, Sc, Sm, Eu). Each sample blank and standard was counted on the first, third and twentieth day after the end of a 10-hr irradiation in the McMaster Nuclear Reactor. Electroncially ingetrated counting data were transferred into a TSR-80 minicomputer programmed to do all necessary calculations and which provided a hard copy of the results.

Total ash on each filter was also determined.

3.8.6 Analysis of Dichotomous Filters

Mass Measurement by β-Attenuation. The mass loading of both fine and coarse particulate matter on the dichotomous sampler filters was determined by β-attenuation. Each mass loading was obtained by measuring the intensity of β-particle emissions from a 147 Pm source transmitted through the filter substrate both before and after the ambient particulate samples were collected.

The mass determinations were carried out in the laboratories of Northup Services Inc. at the Environmental Sciences Research Center, U.S. EPA, Research Triangle Park, North Carolina. The β-attenuation measurements were made using a 500 microcurie 147 Pm source in a completely automated system. Two trays of 36 filters were run at a time. The system configuration is such that the β-radiation passes through the deposit and then through the filter substrate before reaching the detector. The system automatically sequences through the two filter trays plus 5 standards, recording the β-particle count during a 90 sec. interval, in approximately 2 hours.

A complete set of 720 unexposed, numbered filters in 20 filter trays were taken to the Northrup Laboratories and the β-attenuation for each unexposed filter was determined and recorded. After exposure in the field, the exposed filters were again taken to the Northrup Laboratories and the β-attenuation for each exposed filter determined. The mass loadings were proportional to the difference in β-attenuation between the exposed and unexposed filters. The mass of deposited particulate matter was calculated by the following procedure:

- the 5 standards are of deposited particulate matter at 684, 994, 1330, 1539 and 1866 μg cm^{-2} on polycarbonate film. The β-attenuation (N_x) of each Standard (X_{std}) is measured and fit to the equation

  $$\ln N_{std} = \ln N_o + \mu X_{std}$$

  to determine the intercept, $\ln N_o$, and the slope, μ

  Then,

  $$X = \frac{1}{\mu} [\ln N_o - \ln N]$$

for any N and corresponding X

- X_{tare} (= initial unexposed filter measurement) is determined
- $X_{measure}$ (= Final exposed filter measurement) is determined

as before

Thus, $X_{deposit} = X_{measure} - X_{tare}$

and Mass = Area x $X_{deposit}$

Where Area = area of filter. The area must be determined accurately to obtain good mass data.

Concentration is determined by dividing the calculated mass by the air volume sampled, after correction for particle size crossover during sampling (i.e. the amount of fine particles collected with the coarse fraction, and vice-versa).

Full documentation of all β-attenuation determinations on each filter before and after exposure is provided in Appendix E.

3.8.7 Chemical Analysis by X-ray Fluorescence Spectroscopy

Measurements of trace element composition were made using an energy-dispersive X-ray fluorescence spectrometer (227, 228). In this device, an X-ray beam from a tungsten anode excites a secondary fluorescer which in turn excites the sample with its nearly monochromatic characteristic X-rays (229). The three secondary fluorescers used are Cu, Mo and Tb, for which the corresponding anode potentials of the X-ray tube are 35, 50 and 70 kV, respectively. Each sample was analyzed for 5 min with each fluorescer with an electron current of 400 μA in the X-ray tube. The fluorescent X-ray lines emitted by the sample were detected in a lithium-drifted silicon detector which used electronic collimation to enhance the signal above background. The system is able to detect a wide variety of elemen in the atmosphere (228).

The spectrometer system is fully automated, running through two trays of filters at a rate of 2 min per filter. The elemental concentrations were determined by a minicomputer interfaced to the X-ray spectrometer. For the analysis, it was assumed that an observed X-ray spectrum was a superposition of characteristi

X-rays of each individual element in the sample. Individual spectra of 40 pure element standards were accumulated and stored in the computer memory. These individual spectra as well as a stored clean filter background spectrum were compared with the unknown aerosol spectrum using a stripping procedure to determine the concentration of each element (228).

The filters were analyzed for the following 30 elements using this procedure: Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Cd, Sn, Sb, Va, W, Hg and Pb.

3.9 Data Treatment

The scope and general content of the monitoring and analytical programs have been outlined in the preceding sections. After initial decoding and calculations, the monitoring and analytical results from the various components of the study were consolidated into master files with a common time scale based upon the 6-hour sampling periods. As illustrated in Figure 3-25, large volumes of data were collected, necessitating the use of computer techniques for data reduction, storage and assessment.

Data Base Preparation. First, hourly meteorological data as well as bihourly measurements of CO, COH and traffic were reduced to 6-hourly intervals to coincide with the HiVol sampling period for most of the sites. At this point, preliminary assessment of the TSP data with respect to different wind regimes and study periods could be made despite the fact that the data base was not yet complete. The data were incorporated into the six-hour master file as results became available. The completed six-hour file contained analytical results from AA, IC, and NAA determinations for selected sites and times (according to wind regimes) as well as TSP and meteorological measurements. Statistical analyses generally were performed using this data base.

At some of the background sites, it was necessary to use a sampling duration of 12 hours. The dichotomous sampler was also run on this time base. It was therefore necessary to convert the six-hour data file to twelve-hour measurements for compatibility. The twelve-hour TSP and analytical results were added to this mater file. The XRF analyses and the fine and coarse mass determinations for the dichotomous samples made at the EPA laboratories were supplied on tape as a complete file and were used in this format. Employing these two tapes, all remain-

FIGURE 3-25 SUMMARY OF PARAMETERS MEASURED AND CONSTITUENTS ANALYZED

SITE PARAMETER	RDG	MT HOPE	MOE	VICTORIA	CANNON 1	CANNON 2	BAY	EXPT 1	EXPT 2	EXPT 3	EXPT 4	EXPT 5	EXPT 6	EXPT 7	CONT 1	CONT 2	CONT 3	JOHN ST.	OAK ST.	SCHOOL	FARM	STELCO
WIND SPEED	●	●	●							●												
WIND DIRN	●	●	●							●							●					
CO										●							●					
COH										●							●					
EUR. TRACER										●							●					
TRAFFIC				●	●	●	●															
PRECIP	●																					
TSP								□	□	□	□		□		□	□	□	□	□	□	□	□
IP/RP										×							×					
F^-								■		■	■				■		■			■	■	■
CL^-								■		■	■				■		■			■	■	■
NO_3^-								■		■	■				■		■			■	■	■
Br^-								■		■	■				■		■			■	■	■
$SO_4^=$								■		■	■				■		■			■	■	■
Na^+								■		■	■				■		■			■	■	■
NH_4								■		■	■				■		■			■	■	■
K^+								■		■	■				■		■			■	■	■
Eu												●		●								
As												●		●								
Br												●		●								
Co												●		●								
Cr												●		●								
Cu												●		●								
Fe												●		●								
Mn												●		●								
Sb												●		●								
Se												●		●								
Zn												●		●								
Ash												●		●								
Al										▲							▲					
Si										▲							▲					
P										▲							▲					
S										▲							▲					
Cl										▲							▲					
K										▲							▲					
Ca										▲							▲					
Ti										▲							▲					
V										▲							▲					
Cr										▲							▲					
Mn										▲							▲					
Fe										▲							▲					
Co										▲							▲					
Ni										▲							▲					
Cu										▲							▲					
Zn										▲							▲					
Ga										▲							▲					
Ge										▲							▲					
As										▲							▲					
Se										▲							▲					
Br										▲							▲					
Rb										▲							▲					
Sr										▲							▲					
Cd										▲							▲					
Sn										▲							▲					
Sb										▲							▲					
Ba										▲							▲					
W										▲							▲					
Hg										▲							▲					
Pb										▲							▲					
Al										○		●		●			○			○	○	○
Mn								○		○	○	●		●	○		○			○	○	○
Fe								○		○	○	●		●	○		○			○	○	○
Cu								○		○	○	●		●	○		○			○	○	○
Zn								○		○	○	●		●	○		○			○	○	○
Pb								○		○	○	●		●	○		○			○	○	○
Ni								○		○	○	●		●	○		○			○	○	○
Cd										○		●		●			○			○	○	○
Cr										○		●		●			○			○	○	○
V										○		●		●			○			○	○	○
Ti										○		●		●			○			○	○	○
Ca										○		●		●			○			○	○	○
Hg										○		●		●			○			○	○	○

KEY
- ● NAA (+ Met Data)
- ▲ XRF (2 size fractions)
- ■ IC
- ○ AA
- □ TSP
- [illegible]

ing calculations were performed.

3.10 Dispersion Modelling Methodology

3.10.1 Model Selection

The choice of dispersion model for this study was dictated by the following considerations:

a) Available time and resources precluded the implementation and use of a detailed numerical model.

b) Statistical models cannot provide the discriminatory capability for analysis of a complex experiment.

c) Of the analytical models, the PAL model (Petersen (169)) offers the possibility for detailed hour-by-hour input of meteorology and emissions, thus providing the required resolution.

d) PAL is a comprehensive model for the local scale, so that the important components of the TSP loading can be modelled jointly. To carry this out realistically, the modelling is restricted to the local scale (several km) which provides the highest impact on the measurement areas.

The PAL computer code was available from the EPA through the UNAMAP series. However, due to the particular experimental program carried out in Hamilton, the road component was critically evaluated for purposes of this project. In view of this evaluation, it was found necessary to make some modifications to the line source component along the lines suggested by Tao and Keenan (205). The details of the model and modifications as implemented for this study are presented below. Section 3.10.2 is a general description of the model and its' two input files, while 3.10.3 through 3.10.7 contain a detailed discussion of some important aspects and modifications of the model such as the dispersion parameters, wind fields, point, area and line sources and traffic counts.

3.10.2 General Description of the PAL Model

PAL is an acronym for Point, Area and Line source algorithm (169). It is a method of estimating short-term dispersion using Gaussian-plume, steady-state assumptions, for non-reactive pollutants. Of the six source types originally included in PAL (point, area, two types of line sources and two types of curved path sources), only three are used here: point, area, and straight line sources. PAL is not intended as an urban-wide model but rather as a tool for estimating the relative importance of local sources within a restricted geographical area; therefore, only point, area and line sources which are located within 6 km or so of the monitoring stations on Cannon Street are included:

The following general assumptions are made with respect to all three types of sources:

a) The dispersion from point sources is assumed to be a Gaussian, steady-state plume both in the horizontal as well as the vertical dimension; area and line dispersions are estimated by integrating point source contributions.

b) One hourly averaged meteorological conditions are used for each computation separately; independent computations are made for successive hours.

c) Concentrations are additive: The total concentration at a particular location (receptor) is the sum total of the individual contributions from all point, area and line sources.

Descriptions of the computational schemes used for each type of source (point, area, and line) are summarized in Appendix C1.

3.10.3 Application of PAL Dispersion Model

The original version of PAL (U.S. EPA 78124) was modified for this application in several ways, the most important of which will be briefly discussed here. For a detailed discussion of the program, see reference (169).

The Time-independent Input File PAL.DAT. At the beginning of each run, PAL reads a time-independent input file called PAL.DAT which contains the information needed to initiate a run. This information includes the origin of the coordinate system; a list of parameters for up to 30 each of points, areas and lanes of multi-lane line sources; a list of locations of up to 30 receptors; and various other parameters. For a complete description of PAL.DAT see Appendix C2.

The Interactive Sequence. After PAL.DAT is read in, the program inquires about the start and end dates for the present run; the selection of point, area and line sources and receptors to be included; and a selection of the site where the meteorlogical parameters were measured.

The Time-dependent File HYDBASE.DTA. For each hourly computation, PAL reads the following time dependent parameters from the time-dependent input file HYDBASE.DTA: Wind speed and direction at the chosen site; vertical temperature difference (for stability class computations); and hourly traffic counts for each line source. For a complete description and a sample listing of HYDBASE.DTA, see Appendix C3.

3.10.4 The Disperison Parameters σ_Z and σ_y

In a recent publication, Rao and Keenan (205) showed that the dispersion parameters used in the HIWAY model (as well as in PAL) are "unrealistic and need to be modified"; modifications in σ_Z and σ_y were suggested which have been adopted here and PAL has been modified accordingly. Details of the modifications to σ_Z and σ_y are presented below:

$$\sigma_Z^2 = \sigma_{Zo}^2 + \sigma_{Za}^2 \qquad (3.10.1)$$

where σ_{Zo} is the initial line source dispersion parameter which represents the contribution from wake-induced turbulence, and σ_{Za} is the dispersion parameter representing ambient turbulence.

$$\sigma_{Zo} = 3.57 - 0.53\ U_\perp \qquad (3.10.2)$$

where: $U_\perp$ = cross line wind speed (m sec^{-1})

If $U_\perp > 3.91$ m sec^{-1}, $\sigma_{Zo} = 1.5$ m

σ_{Za} is dependent upon the stability class as follows:

TABLE 3-5

Vertical Dispersion Parameter as a Function of Stability

σ_{Za}	Stability Class
$110.62X^{0.93198}$	a;b;c; (unstable)
$86.49X^{0.92332}$	d (neutral)
$61.141X^{0.91465}$	e;f; (stable)

where X is the upwind distance between the receptor and line source in km.

The crosswind dispersion parameter σ_y is given by

$$\sigma_y^2 = \sigma_{yo}^2 + \sigma_{ya}^2 \qquad (3.10.3)$$

where

$$\sigma_{yo} = 2\sigma_{Zo} \qquad (3.10.4)$$

and

$$\sigma_{ya} = 1000 \sin\theta/(2.15 \cos\theta) \qquad (3.10.5)$$

σ_{ya} is dependent upon the stability class as follows:

TABLE 3-6

Cross-wind Dispersion Parameter as a Function of Stability

θ Appearing in equ.	Stability Class
(18.333-1.8096lnX)/57.2958	a;b;c; (unstable)
(14.333-1.7706lnX)/57.2958	d (neutral)
(12.5-1.0857lnX)/57.2958	e;f; (stable)

In all above equations, both σ_Z and σ_y are in meters.

3.10.5 Meteorological Data

The following table summarizes the meteorological data available for PAL runs on an hourly basis as part of the time-dependent HYDBASE.DTA file.

TABLE 3-7

Summary of Meteorological Data

Site No.		Height in m.	Speed	Wind Direction	Temp.	∂T/∂Z
1	Woodward Tower	10	✓	to 1°	✓	✓
2	Woodward Tower	61	✓	"	✓	
3	Royal Botanical Gardens	10	✓	"	✓	no
4	Mount Hope	10	✓	"	✓	"
5	Exp. 3	10	✓	16 points	✓	"
6	Cont. 3	10	✓	8 points	✓	"

Stability class was always computed using $\partial T/\partial Z$ data from the Woodward Street tower between the 10 and 61 meter height; wind speed and direction, as well as temperature, were specified separately for each run during the interactive sequence by choosing the site number to be used during the specific run. The cut-off value for minimum wind speed was set at 1.0 m sec^{-1}, so that if the wind speed value read from HYDBASE.DTA for the particular hour being computed was less than 1.0 m sec^{-1}, it was set at 1.0 m sec^{-1}.

3.10.6 Point Sources

Emission rates for point sources were provided by the Ontario Ministry of the Environment. At the time of conducting the microinventory study (see section 3.2), the most recent emission data available was for the year 1974. Data for 1979 subsequently became available (coinciding with the experimental period of the study) and these more current emission rate data have been used in the dispersion modelling studies.

Table 3-8 shows the sixteen point sources used in both the microinventory and mathematical modelling portions of the study. As can be seen, the emission rates of some sources changed considerably between 1974 and 1979 and these changes must be considered in any detailed comparison of the microinventory and dispersion results.

Although the microinventory used data for 16 sources from the MOE compilation (224), these 16 sources were in fact composed of a number of sub-sources with different characteristics (such as stack height, diameter or emission temperature). After grouping similar sub-sources within each of the 16 original point sources shown in Table 3-8, a list of 30 point sources as shown in Table 3-9 resulted. For a more complete list of the 30 point sources characteristics, see Appendix C2 (PAL.DAT).

PAL was modified with respect to treatment of point surces in that if for a particular hour the emission temperature of the point source was less than the ambient temperature, the point source was not omitted from the computation, but the emission temperature was set to be equal to the ambient temperature and the computation carried out.

The initial σ_y and σ_z were taken as zero in case of stacks (small diameter to height ratio); however, when the point source was in fact a building

TABLE 3-8

Point-source Emission Rates Used In Dispersion Modelling Studies*

No.		MOE Data (Tons/Year) 1974	1979	± % diff.
1	Canron	131.2	119.3	- 9
2	Stelco Steam Plant	102.1	21.8	-79
3	Stelco Blast Furnace	702.6	547.3	-22
4	Stelco Coke Quench	160.6	146.0	- 9
5	Stelco Sinter Plant	1,512.6	1,246.4	-18
6	Stelco Coke Oven	1,025.8	885.4	-14
7	Stelco Coal Handling	490.6	460.4	- 6
8	Stelco B.O.F.	496.4	545.2	+10
9	Stelco Open Hearth	885.5	625.7	-29
10	Proctor & Gamble	258.9	387.0	+49
11	Dofasco B.O.F.	1,241.0	505.7	-59
12	Dofasco Coke Ovens	727.4	635.4	-13
13	Dofasco Blast Furnace	494.7	405.5	-18
14	Dofasco Coke Ovens	618.2	199.1	-68
15	National Steel Car	98.8	89.2	-10
16	Interflow Systems	200.0	200.0	0
	Total	9,146.4	7,019.4	-23

* Data from Ontario Ministry of the Environment 1974 and 1979 Emission Inventories. Subsequent to running the dispersion model calculations it was determined that Interflow Systems was not operating during the study period.

TABLE 3-9

The 16 Point Sources Sorted by Common Sub-Source Characteristics

Source No.	Name	Source No.	Name
1	Canron #1	16	Stelco Open Hearth #1
2	Canron #2	17	Stelco Open Heatth #2
3	Stelco Steam Plant	18	Proctor & Gamble
4	Stelco Blast Furnace	19	Dofasco B.O.F. #1
5	Stelco Coke Quench	20	Dofasco B.O.F. #2
6	Stelco Sinter Plant	21	Dofasco Coke Ovens #1
7	Stelco Coke Ovens #1	22	Dofasco Coke Ovens #2
8	Stelco Coke Ovens #2	23	Dofasco Blast Furnace #1
9	Stelco Coke Ovens #3	24	Dofasco Blast Furnace #2
10	Stelco Coke Ovens #4	25	Dofasco Blast Furnace #3
11	Stelco Coke Ovens #5	26	Dofasco Coke Ovens #1
12	Stelco Coke Ovens #6	27	Dofasco Coke Ovens #2
13	Stelco Coal Handling	28	Dofasco Coke Ovens #3
14	Stelco B.O.F. #1	29	National Steel Car
15	Stelco B.O.F. #2	30	Interflow Systems

(similar horizontal and vertical dimensions), then

$$\sigma_{yo} = \text{building width}$$

$$\sigma_{Zo} = \tfrac{1}{2}\ (\text{building height})$$

As can be seen from the listing in the appendix, this happended in 12 out of 30 point sources.

3.10.7 Area Sources

The microinventory study divided the area sources around each receptor location (Experimental, Control, etc.) into 13 sections of 3 concentric circles with 0.25, 0.5 and 1.0 mile radii from the receptor (see Section 3.2, Figure 3-3). Since in PAL area sources must be specified as squares or rectangles, the 13 circular areas were projected into 16 squares of 800 x 800 m each, as shown in Figure 3-26, and the source strength for each of the 16 squares, for both the Experimental and Control sites, was computed.

The microinventory study showed that reentrainment road dust as well as exhaust particulate emissions were contributing factors to the area sources. Since PAL computes line contributions to the concentrations at the receptors separately, it was necessary to exclude these factors from the 16 area sources which served as input to PAL. This was done by subtracting the traffic-generated contributions of each street segment modelled explicitly by the line source sectio in PAL, to each of the 16 areas. A value of 3.18 g/vehicle km was used together with average traffic counts for each of the three streets involved (for details see the following section on line sources). The results of this subtraction are presented in Tables 3-10, and 3-11 for the Control and Experimental sites, respectively.

Some trial runs were made for which the four closest areas (#13 through #16 in Figure 3-26) were each divided into four parts by projecting and repartitioning the appropriate contributions of the circular area sections of the microinventory data base; this resulted in 28 (rather than 16) area sources. There were no appreciable differences in the computed concentrations at the various receptors between these trial runs and similar runs with 16 equal square areas; on the other hand, the differences in computer time were considerable. As a result of this experiment, it was decided to leave the distribution of area

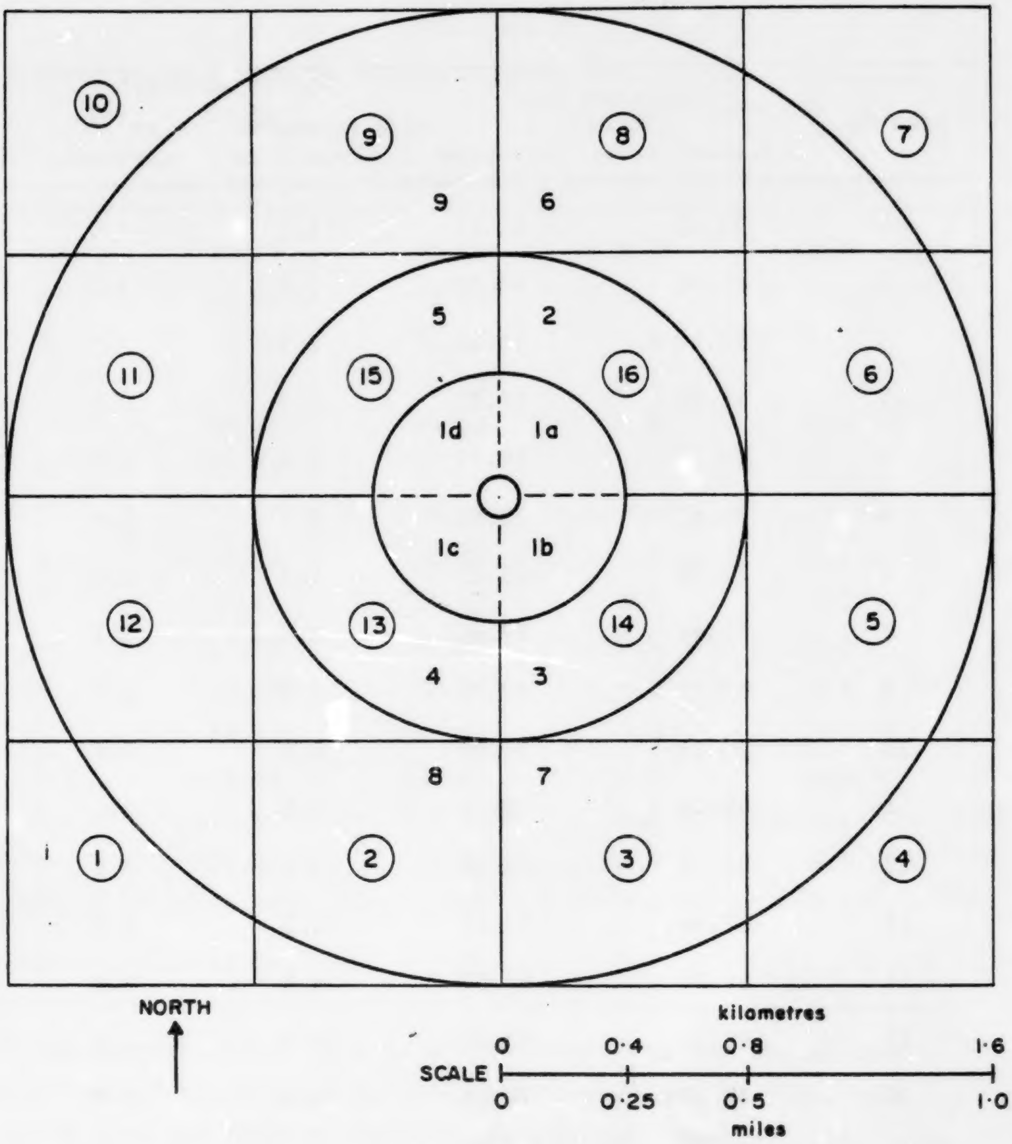

⑩
⑨
⑧
⑦
9
6
5
2
⑪
⑮
⑯
⑥
1d
1a
1c
1b
⑫
⑬
⑭
⑤
4
3
8
7
①
②
③
④
NORTH
kilometres
0
0·4
0·8
1·6
SCALE
0
0·25
0·5
1·0
miles

FIGURE 3-26 STANDARD SECTORS USED IN MICROINVENTORY (CONCENTRIC CIRCLES) AND IN P.A.L (16 SQUARES)

TABLE 3-10

The 16 Area Sources Around The Control Site

Area No.	Emission Rate (Tons/Yr.)		Source Strength (g $sec^{-1}m^{-2}$ x 10^{-6})	
	Streets in	Corrected	Streets in	Corrected
1	21.42	21.25	1.1	1.0
2	64.26	63.75	3.2	3.2
3	50.40	50.40	2.5	2.5
4	16.80	16.80	0.8	0.8
5	49.11	49.11	2.4	2.4
6	75.67	75.67	3.8	3.8
7	25.89	25.89	1.3	1.3
8	77.66	77.66	3.8	3.8
9	60.77	50.56	3.0	2.5
10	20.26	16.86	1.0	0.8
11	59.21	49.26	2.9	2.4
12	62.61	62.11	3.1	3.1
13	87.66	82.12	4.3	4.1
14	64.26	62.57	3.2	3.1
15	81.51	63.80	4.0	3.2
16	72.65	70.06	3.6	3.5
TOTAL	890.14	837.86		

Here the reduction is 5.9% for all areas, and 9% when only the four closest areas are considered.

TABLE 3-11

The 16 Area Sources Around The Experimental Site

Area No.	Emission Rate (Tons/Yr.)		Source Strength $(g\ sec^{-1} m^{-2}$ x $10^{-6})$	
	Streets in	Corrected	Streets in	Corrected
1	20.67	20.67	1.0	1.0
2	62.02	62.02	3.1	3.1
3	99.20	91.57	5.0	4.5
4	33.07	30.52	1.7	1.5
5	96.65	89.22	4.8	4.4
6	31.59	31.01	1.6	1.5
7	10.81	10.61	0.5	0.5
8	32.43	31.82	1.6	1.6
9	34.10	34.10	1.7	1.7
10	11.37	11.37	0.6	0.6
11	33.22	33.22	1.7	1.6
12	60.43	60.43	3.0	3.0
13	131.48	122.36	6.6	6.0
14	144.23	128.75	7.2	6.3
15	94.87	90.57	4.7	4.5
16	66.90	62.84	3.4	3.1
TOTAL	963.04	911.08		

As can be seen, there is a reduction of 5.4% in the annual area emissions if the contributions of the appropriate sections of Cannon, Bay and Victoria streets are removed. However, this reduction increased to 7.5% if only the four closest areas to the receptor site (#13 through #16) are considered.

sources at 16 equal squares. For a detailed listing of area source characteristics see Appendix C2.

3.10.8 Line Sources

Cannon, Bay and Victoria Streets were treated by PAL as line sources. Each was introduced in two sections, as follows: Cannon West between Oak Street and Ferguson Avenue and Cannon East between Ferguson and Bay Street; Victoria Avenue South between Main and Cannon, and Victoria North between Cannon and Birge Street; Bay Street South between Main and Cannon and Bay North between Cannon and Stuard Street. The reasons for introducing each of these three streets in two sections were different in each case: for Cannon there are two traffic counting stations at Experimental (Cannon between Park and Bay) and at Control (Cannon and Victoria); Bay changes direction as well as width at its intersection with Cannon; Victoria changes its width at Cannon. These segments are summarized in Table 3-12 below.

TABLE 3-12

Street Segments Introduced As Line Sources In PAL

Line No.	Section Name	Length, km.
1	Cannon West	1.015
2	Cannon East	0.750
3	Victoria North	0.655
4	Victoria South	0.650
5	Bay North	0.440
6	Bay South	1.115

Traffic counts were carried out on an hourly basis in Cannon West, Cannon East, Victoria and Bay during July and one week in the beginning of September, and were used in the hourly computations of line source contributions during these periods. For the rest of the experimental period, which also included most of June and all of August, traffic counts were averaged over existing data per street, day-of-the-week, and hour-of-the-day. A complete tabulation of these average values is given in Appendix C4.

Emission factors for reentrained dust and exhaust particulates were derived from EPA data (54) as follows:

Reentrained Dust

Car: 3.15 g per vehicle mile = 1.97 g per vehicle km

Truck: 6.78 g per vehicle mile = 4.24 g per vehicle km

Exhaust particulates for city centre conditions (average speed 31.6 km/hr); ambient temperature 24°C; vehicle mix 63:32:2.5:2.5 ≡ cars: light trucks: heavy gasoline trucks: diesel trucks, or approximately 63:37 = cars: trucks. Under these conditions the exhaust particulates emission rate is quoted as 0.37 g per vehicle km. Therefore the total vehicle-generated particulates is:

	63% of 1.97×10^{-3} g per vehicle metre
plus:	37% of 4.24×10^{-3} g per vehicle metre
plus:	0.37×10^{-3} g per vehicle metre
TOTAL EQUALS	3.18×10^{-3} g per vehicle metre

When multiplied by the traffic count (in units of vehicle per sec), this factor yields the line source strength in units of g $sec^{-1} m^{-1}$. A complete listing of line source parameters is provided in Appendix C3.

Several trial runs of PAL with each street represented by the appropriate number of lanes resulted in a considerable increase in computer time per run, but showed no appreciable differences in line source contributions to computed receptor concentrations; subsequently, all PAL runs were carried out with each of six street segments being treated as a single lane.

3.11 Receptor Modelling Methodology

As discussed in Section 2.6, chemical element mass balance, or chemical mass balance (CMB) for short, was chosen to assist in interpreting the data from the Hamilton study. The following outlines the methodology used as reported by Cooper and Watson, 1980 (206).

The basic principles of the CMB method as first presented by Friedlander (230,231) are illustrated schematically in Figure 3-27. The CMB method assumes that the aerosol chemical and physical parameters are conserved from the time a chemical species is emitted from its source to the time it is measured at a receptor. That is, if p sources contribute M_j mass of particles to the receptor, then

$$m = \sum_{j=1}^{p} M_j \tag{3.11.1}$$

where m is the total mass of the particulates collected on a filter at a receptor site.

The mass of a specific chemical species, m_i, is given by the following:

$$m_i = \sum_{j=1}^{p} M_{ij} = \sum_{j=1}^{p} F'_{ij} M_j \tag{3.11.2}$$

where M_{ij} is the mass of element i from source j and F'_{ij} is the fraction of chemical species i in the mass from source j collected at the receptor. It is assumed that the chemcial and physical characteristics of each individual chemical component are conserved so that

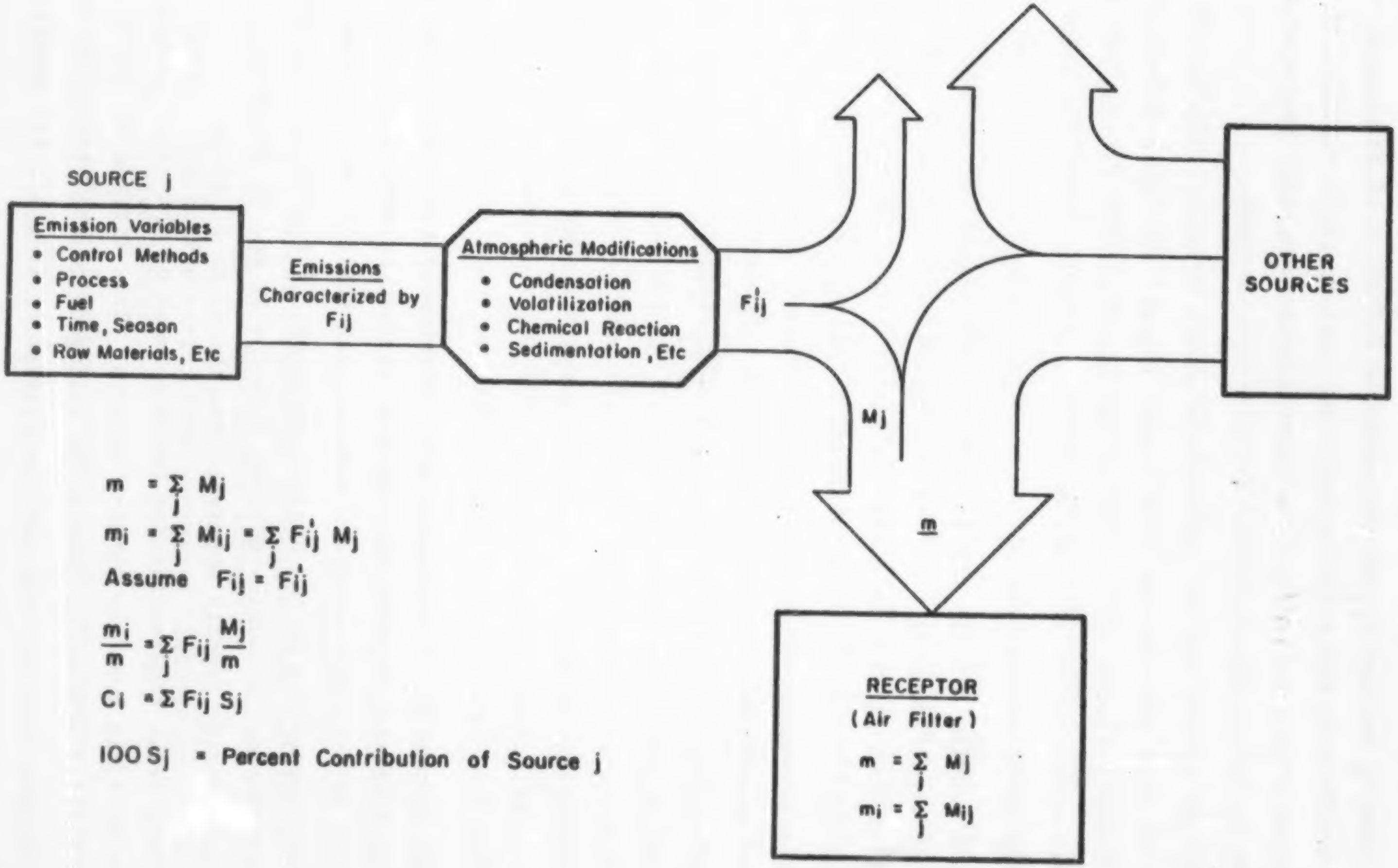
$$F'_{ij} = F_{ij} \tag{3.11.3}$$

where F_{ij} is the fraction of chemical i emitted by source j as measured at the source. (This same assumption is required for at least one of the elements from each source determined with factor analysis.) The degree of validity in this assumption depends on the chemical and physical properties of the species and its potential for atmospheric modifications such as condensation, volatilization, chemical reactions, sedimentations, etc.

Accepting this assumption, it then follows that:

$$C_i = \sum_{j=1}^{p} F_{ij} S_j \tag{3.11.4}$$

where C_i is the fraction of the chemical component i measured at the receptor (air filter) and S_j is the source contribution; i.e., the ratio of the mass contributed from source j to the total mass collected at the receptor site. In practice, it is this fraction of particulate pollution measured at a receptor due to source j, S_j, which is of primary interest in CMB calculations.


SOURCE j
Emission Variables
• Control Methods
• Process
• Fuel
• Time, Season
• Raw Materials, Etc
Emissions
Characterized by Fij
Atmospheric Modifications
• Condensation
• Volatilization
• Chemical Reaction
• Sedimentation, Etc
F'ij
Mj
m
OTHER SOURCES
RECEPTOR
(Air Filter)

$$m = \sum_j M_j$$

$$m_i = \sum_j M_{ij} = \sum_j F'_{ij} M_j$$

Assume $F_{ij} = F'_{ij}$

$$\frac{m_i}{m} = \sum_j F_{ij} \frac{M_j}{m}$$

$$C_i = \sum F_{ij} S_j$$

$100 S_j$ = Percent Contribution of Source j

$$m = \sum_j M_j$$

$$m_i = \sum_j M_{ij}$$

FIGURE 3-27 SCHEMATIC REPRESENTATION OF CHEMICAL MASS BALANCE PRINCIPLES.

If the C_i and the F_{ij} at the receptor for all p of the source types suspected of affecting the receptor are known, and $p < n$ (n = number of chemical species), a set of n simultaneous equations exists from which the source type contribution S_j may be calculated by least squares methods.

The CMB method applies the maximum amount of source information to resolve the sources contributing to a single filter. Although normalized elemental source patterns can be used in the least squares fitting procedure, the abosolute concentration of at least one of the elements from each source type must be know for a quantitative analysis.

This fitting process can be more readily visualized by plotting both the source and ambient elemental patterns on semilogarithmic paper. The atomic number is plotted in historgram form along the linear axis while the elemental composition, either μg/m^3, percent or normalized, is plotted on the logarithmic axis. In this way, the geometric shape of the distribution is independent of its level of contribution and can be considered similar to a fingerprint.

The source elemental fingerprints or spectra illustrate the unique pattern many sources exhibit. Some sources, however, do not exhibit unique patterns and must be grouped into source types. Although there are distinct differences in the percent composition for some of the major elements, they cannot be resolved as distinct sources from an ambient aerosol composed of a complex mixture of sources in the method's current stage of development.

The complexity of these patterns increases significantly when material from several different sources are combined to form an ambient aerosol. The presence of some of the major sources, however, can still be easily identified by a simple visual inspection of the ambient patterns. For example, the automotive exhaust contribution is usually obvious from the Br and Pb components. The soil component is normally readily apparent from the Al to Si ratio.

Using least squares fitting methods, most of the major sources can be resolved or stripped from the ambient spectra. This fitting of source distributions to a complex mixture of sources is analogous to the fitting or stripping of standard NaI (Tl) γ-ray spectra (energy histogram) from a γ-ray spectrum of a complex mixture of radionuclides.

Sources resolved from the ambient elemental spectra are not necessarily the unique solution. They are instead the best set of sources which, when combined in the appropriate relative contributions, come closest to reproducing the observed ambient elemental pattern. Absolute percent concentrations are not required to resolve sources and determine their fractional contribution to the ambient elemental pattern. The absolute percent composition for at least one element or component in both the source and ambient aerosol, however, is required for a quantitative determination of source's fractional contribution.

The most significant limitation to source resolution with the CMB method is the uncertainty (noise) in the F_{ij} values which can vary with time, location, raw materials, fuel type, etc. In the past, very little chemical data on source emissions were available. The catalogue of source characteristics, however, is growing, and as it does, so will the method's source resolving power.

Source resolution can also be improved by measuring additional components and by reducing the uncertainty in the measured components in both the ambient and source particulates. The most cost effective set of components, however, have not yet been determined but will certainly depend on the sources expected to be major contributions to each airshed studied.

In this study CMB model calculations were carried out by NEA Laboratories Inc. on 55 dichotomous data sets (110 filters). Ten source fingerprints were selected for possible fitting. These were:

1. RDUST - The road dust source matrix as determined for Hamilton road dust. Source: chemical analysis of Hamilton road dust samples.
2. TRANS - The chemical fingerprint associated with vehicular exhaust. Source: NEA Inc. source library.
3. INCINR - The source matrix from municipal incineration. Source: NEA Inc. source library.
4. LIMEST - Crustal limestone. Source: NEA Inc. source library.
5. RSDOIL - Residual oil combustion. Source: NEA Inc. source library.
6. SECSO4 - Secondary sulphate($(NH_4)_2SO_4$).

7. BOF - Basic oxygen furnace. Source: chemical analysis of precipitation sludge, MOE.
8. BLAST - PACS Blast furnace. Source: NEA Inc. source library.
9. BLSTF - Blast furnace. Source: cast house emission dust chemical analysis, MOE.
10. COMP - Iron and Steel Composite. Source: CMB Analysis, Radiation Centre of Osaka Prefecture, Japan.

Of these ten sources, typically four to six were fit to a given filter. The sources fit along with their predicted contribution to the total measured ambient mass concentration in $\mu g/m^3$ and percent were calculated for each filter. The chemical species used in the CMB program, their measured concentration in $\mu g/m^3$, the percent their measured concentration is of the total ambient concentration, the predicted (or calculated) value determined from the CMB program and the ratio of the calculated value to the measured value were all determined.

A predicted concentration for the non-fitting chemical species were calculated with the CMB program but they were not involved statistically in determining the best fit. Chemical species for which there were missing data, that had "less than" or very low concentration values or which are often associated with sampling artifacts (e.g., Cu) are generally not used as fitting elements. For example, in this study, chromium was only used for a fitting element with a portion of the filters when its concentration was substantially above the uncertainty level. When a low concentration or a "less than" value was encountered, chromium was removed from the list of fitting elements. Because corresponding ambient data were not available for SO_4^{2-}, NO_3^-, VC (volatilizable or organic carbon) or NVC (nonvolatilizable or elemental carbon) at the time the CMB calculations were run, they were not included as fitting elements but a predicted value was determined for them. The elements Co, Ga, Ge, As, Se, Rb, Sr, Cd, W and Hg were not used in the CMB program because of their low ambient concentrations The elements P and Ba were not used because of the combination of their relatively low concentration and the fact that many of the source matrices used did not have a chemical fingerprint for them.

The quality of a CMB fit is determined by three factors:

(1) The reduced chi square

(2) the ratio of the calculated to measured values for each major chemical species, and

(3) the percent of the total measured ambient concentration which is explained.

Each of these parameters were included in the results for each filter. The closer the reduced chi square is to zero and the closer the calculated to measured ratios are to one, the better is the CMB fit. Moreover, the greater the fraction of the total ambient concentration which is explained the better is the CMB fit. However, 20 to 40 percent unexplained mass is common due to elements which are not included in source or ambient analyses, viz., H, O, N, C.

It should be emphasized that the sources fit in a CMB program are not a unique set of sources but rather those which best meet the three previously mentioned criteria. The less well characterized the sources are in a given airshed, the greater is the chance for an improper fit. Detailed chemical analysis of each major particulate source in an airshed is necessary to insure accurate CMB results. CMB studies which are illustrative in nature can be accomplished by using source fingerprints obtained from other airshed studies such as has been done here, however, care must be used in the interpretation of the results achieved.

The study was enhanced by the collection and analysis of road dust samples in the Hamilton study area in order to provide a good elemental matrix for this particle source. An XRF scan of seven bulk (< 400 mesh) road dust samples revealed three potential groupings based on small differences in the Fe/Si, Ni/Si, Cu/Si, Pb/Si and Cl/Si ratios. Three composite samples were formed, resuspended and size sampled onto dichotomous filters and analyzed. It was determined that the differences were too subtle to distinguish between them with CMB source apportionment and a single weighed average source matrix was formed for both the fine and coarse fractions as defined by the dichotomous sampler.

4. RESULTS

The scope, design and methodologies of the study have been described in preceding sections. In this section, the results obtained from the various components of the study are presented in summary form with brief commentary on the more apparent and general features of the data. Detailed tabulations of the data in the Appendices also are cited where appropriate. In the subsequent section, the results are discussed in more detail and with specific reference to the primary objectives of the study;

- characterization of particulate matter at the study area
- identification of major sources
- evaluation of control technologies.

4.1 Microinventory Results

As discussed in Sections 2.3 and 3.2, the microinventory approach is used to quantify the relationship between particulate emissions, monitor siting characteristics, and experimentally measured ambient TSP levels. The method is empirical, using a regression equation to relate the above variables. The data base used to originally develop this method was compiled by the U.S. EPA through various studies (Section 2.3), and is based on data from 79 sites in four urban areas (Portland, Oregon; Birmingham, Alabama; and the St. Louis and Kansas City Metropolitan areas) (232-235). Subsequent microinventory data have been used to validate the technique (236).

The form of the method is a multiple linear regression equation with annual geometric mean TSP concentration as the dependent variable and four independent variable terms:

1) AREA, annual area source particulate emissions within on mile (including fugitive dust and influence of monitor height);
2) POINT, annual point source emissions within five miles;
3) LOCAL, local sources (those traffic related sources within 200 feet of the monitor);
4) VISPLUME, an indicator variable of 0 or 1 to reflect the presence of a visible plume of resuspended dust resulting from passing traffic on the nearest streets. This term is usually only

significant for unpaved roads.

Pace (51) selected these variables after examination of the correlation matrix for approximately 30 potential variables. Multiple regression was used to derive the coefficients for each of the terms in the equation and to obtain the statistical values used to judge the accuracy of the regression equation.

The regression equation is given by:

$$\text{AVGAQ} = C_1\ (\text{Area}) + C_2\ (\text{Point}) + C_3\ (\text{Local}) + C_4\ (\text{Visplume}) + K_i\ (\text{"city effects" variables}) \qquad (3.5.1)$$

where AVGAQ = Predicted annual geometric mean TSP, $\mu g/m^3$

$$\text{AREA} = \frac{A_1}{0.0324} \cdot \frac{25}{\text{HGT}} + \frac{(A_2 + A_3 + A_4 + A_5)}{0.16} + \frac{(A_6 + A_7 + A_8 + A_9)}{0.6084} \qquad (3.5.2)$$

The constants 0.0324, 0.16 and 0.6084 are the square of the radius in miles to the area weighted centre of the annular ring defined by the sectors in the numerator.

A_i = Total area source emissions in Section i, ton/yr

HGT= Height of sampler, ft.

$$\text{POINT} = \sum_{i=1}^{n} \frac{\text{PSEM}_i}{D_i^2}\ (\text{WWF}) \qquad (3.5.3)$$

n = number of point sources within 5 miles

PSEM_i = Emissions from point source i, ton/yr

D_i = Distance to point source i, miles (lower limit 0.5 miles)

WWF = Wind weighting factor, computed as annual wind direction frequency of occurrence (%) in quadrant where source is located, divided by 25, dimensionless.

$$\text{LOCAL} = \frac{\ln \text{ADT}_1}{\sqrt{\text{HGT}^2 + \text{DIS}_1^{\ 2}}} + \frac{\ln \text{ADT}_2}{\sqrt{\text{HGT}^2 + \text{DIS}_2^{\ 2}}} + \ldots\ldots \qquad (3.5.4)$$

ADT_i = Average daily traffic on nearby road i, veh/day

DIS_i = Distance to road i, ft. (upper limit of DIS_1 is 200)

VISPLUME = 0 if no visible plume of resuspended dust results from passing traffic on paved roads, 1 if there is a plume

K_i (city effects) = Regression constant

C_i = Regression coefficients.

Evaluations of the applicability and stability of this equation have been discussed by Pace (51). The first terms in this equation are straightforward estimates of discrete groups of sources of particulate emissions. Since there were no visible plumes along the streets in the study area, the VISPLUME term was set equal to zero in all cases. The "city effects" respesents that portion of the concentration which is assumed to be relatively constant across the study area and is not accounted for by the other terms in the regression equation.

The three types of compilations used to input to this regression equation are for area source contributions at each site, point source contributions at each site, and local, traffic-related, contributions at each site. The methods used to compile data relevant to the sources surrounding the experimental site have been described in Section 3.2.

Compilations of fugitive dust sources were obtained as follows: for cleared areas, storage areas, construction/demolition sites, agricultural activities and railyards, the estimated area in acres was multiplied by the appropriate emission factor from Table 3.1, and summed for each sector within the 1 mile microinventory area around each monitoring site. For unpaved parking lots, the numbers of cars using the lot annually was estimated and multiplied by twice the average distance to the centre of the lot to arrive at an activity rate for the lot. This was then multiplied by the appropriate emission factor to arrive at annual emissions. The emissions were summed for each sector as before. The activity rate for unpaved roads and laneways was estimated from traffic count and length of roadway within a particular sector, and then multiplied by the appropriate factor as before. These emissions were again summed for each sector. In the case of reentrained dust from streets, a slightly different approach was used. The auto and diesel truck emissions listed in the Hamilton Area Source Inventory (225) were converted back to VMT. These data were then apportioned to each sector by estimating the proportion of the sector within each 1 km square UTM grid and summing the various contributions to each sector. The total reentrai ment caused by automobiles and diesel trucks were then calculated using the appropriate emission factor from Table 3-1. Detailed listings of area source contributions are listed in Tables B-1 to B-8 in Appendix B. This latter source proved to be the dominant component of area emissions.

Combustion emissions were obtained from the Hamilton Area Source Inventory (225). These summaries were used to calculate an AREA value for each sampler, and these values are listed in Table 4-1. The AREA values for Experimental 3, 4 and 6 are reported as identical because these samplers are too close together to distinguish differences within the scale of the area source compilations (1 mile radius).

The point source contributions and other location parameters used to calculate POINT values for each site are listed in Appendix B, Table B-9. The calculated POINT values for each monitor are listed in Table 4-1. In this Table, Experimental 1, 2, 3, 4, 6 and Control 1, 2 and 3 considered identical on the scale of the point source compilation (5 mile radius).

The data for monitor height, distance from the road and the natural logarithm of average daily traffic (ADT) are compiled for each sampler in Appenix B, Table B-10, with the calculated value for LOCAL at each site. These calculated values for LOCAL are listed for each monitor in Table 4-1. For the background site at School, Farm and Stelco Research Centre (SRC), no LOCAL contributions were identified.

The detailed data in Table B-8 (Appendix B) shows that reentrained road dust is the predominant source at all sites, ranging from 58% of total area emission at the Cannon Street sites to 65% at the Farm, 70% at the School and 82% at the SRC site. However, the largest reentrained road dust contributions are at the Cannon St. sites. This is expected as these sites are in the centre core of the city and also have the highest contributions from other area source types. Reentrained street dust contributions at the School site are almost entirely due to the effect of the Queen Elizabeth Way (QEW) with ADT levels of approximately 50,000 vehicles at this point. Similarly, the SRC site is affected by the nearby junction of QEW and Highway 402 with combined ADT levels of close to 100,000

TABLE 4-1

Summary of Source Contributions for Microinventory Regression Equation Determination

Site	Area	Point	Local	Measured Mean ($\mu g/m^3$)	
				Study Period	Annually Adjusted
Experimental 1	4,174	2,422	0.2258	76	65
Experimental 2	5,408	2,422	0.3578	84	71
Experimental 3	8,046	2,422	0.5213	95	81
Experimental 4	8,046	2,422	0.1471	80	68
Experimental 6	8,046	2,422	0.0894	78	66
Control 1	3,059	2,148	0.2808	82	70
Control 2	3,778	2,148	0.4230	88	75
Control 3	5,308	2,148	0.6156	99	84
John Street	6,719	1,998	0.6101	109	93
Oak Avenue	5,455	2,379	0.8576	105	89
School	1,896	4,622	0	77	75
Farm	602	0	0	59	50
Stelco Research Centre	1,166	50	0	47	40

TABLE 4-2

Comparison of Annual Average TSP Loadings Predicted by Microinventory Calculations with Observed Values

Site	Microinventory Contributions ($\mu g/m^3$)				Geom. Av. TSP ($\mu g/m^3$)	
	Area	Point	Local	Sub Total	Predicted[a]	Measured[b]
Expt. 1	19	2	11	32	77	78
Expt. 2	24	2	18	44	89	84
Expt. 3	36	2	26	64	109	95
Expt. 4	36	2	7	45	90	80
Expt. 6	36	2	5	43	88	78
Control 1	14	2	14	30	75	82
Control 2	16	2	21	39	84	88
Control 3	24	2	31	57	92	99
John St.	30	2	31	63	108	109
Oak St.	25	2	43	69	114	105
School	7	4	0	13	58	77
Farm	3	0	0	3	48	59
Stelco Research Centre	5	0	0	5	50	47

[a] Calculated according to Pace regression equation:

$$\text{Geom. Av. TSP} = [0.00451(\text{AREA}) + 0.00096(\text{POINT}) + 50.5(\text{LOCAL}) + 45] \pm 11\ \mu g/m^3$$

$$(r = 0.876,\ r^2 = 0.767)$$

[b] Values measured during the study period

vehicles. In contrast, the Farm site is located near residential areas and thus reentrained street dust makes a much smaller contribution.

Point sources emit approximately 9,000 tons/year of particulate matter in the vicinity of Cannon St. sites and the School site (Table B-8). For the Cannon St. sites, this can be compared to approximately 1,000 tons/year of emissions from area sources. However, because of the relative proximities of the two types of sources, to the particular sampling sites, the point sources are not expected to have as large an effect on local TSP levels as the area sources. Of these Cannon St. sites, the Control and Oak Ave. sites should be affected to a larger degree because they are closer to the point sources. The School site is even closer to the point sources and also lies downwind of these sources from the prevailing southwesterly winds. Thus, it would be expected to receive the greatest point source contribution. The Farm site is not at all affected by local point sources, and the SRC site only minimally.

Thus, the Cannon St. sites are expected to be influenced by predominantly area and local traffic-related sources, the School site mainly by area and point sources, and the Farm and SRC sites by neither. Therefore, the Farm and SRC sites reflect background concentrations.

The regression equation (Equation 3.5.1) developed by Pace (51) using data from 79 sites in the U.S. can be used in conjunction with the inventory data in Table 4.1 to predict annual average TSP loadings. This involves the assumption that the relationship between source emissions and observed loading in Hamilton is similar to that for the cities involved in the U.S. studies. The annual average TSP loading calculated in this way using the microinventory for the 13 HiVol monitors at 7 sites in Hamilton are presented in Table 4.2. Site nomenclature is as outlined in Section 3 (Figure 3-20).

The standard deviation of the regression is ± 11 $\mu g/m^3$, and this can be taken as an indication of good agreement between observed and predicted TSP levels. Furthermore, it can be seen from Table 4.2 that the predicted and measured values agree well except for the monitors at Experimental 3 and the School. In the case of the Experimental 3 monitor, the measured value is 14 $\mu g/m^3$ lower than predicted.

For the School monitor, the measured values is 19 $\mu g/m^3$ higher than predicted. A possible cause for this is that the coefficient of the POINT term in the regression equation is too low relative to the Hamilton area. The School site is expected to receive a larger contribution from the point sources along the harbour shore because of the predominant SW winds carrying particulates towards this site and also because the sources are closest to this site.

The relatively good fit obtained for the Hamilton data confirms the general applicability of the microinventory approach. The good fit also suggested the possibility that the data obtained in the Hamilton study would permit a direct determination of coefficients in the regression equation resulting in an equation more specific to the study area. Such an equation could be expected to give a more quantitative definition of the relative importance of the various source categories in the area provided that the coefficients can be determined with adequate precision using data from only 13 monitoring sites.

Multiple regression analyses were carried out using the three terms listed in Table 4-1 as independent variables, and geometric mean TSP values, calculated in two ways, as the dependent variable. In the first calculation, geometric mean TSP values for the study period were used as listed in Table 4-1. In the second calculation, the study period mean TSP values were adjusted to annual means using scaling factors obtained as ratios from MOE HiVol data for 1974 to 1978. Using this data, the ratio was calculated between average TSP values for the months of June, July and August and average annual TSP values for 9 MOE monitoring sites in Hamilton. The ratios for these MOE sites were grouped to obtain average ratios for the Cannon Street and the School monitoring sites. It was found that the MOE sites around the Cannon St. sites had an average ratio of annual average TSP to three month summer average TSP of 0.85, and the one site near the School site had a ratio of 0.97. The annual adjusted mean TSP values calculated using these ratios are listed in Table 4-1. The Farm and SRC sites were assumed to have ratios similar to the Cannon St. sites.

Summary statistics for the two regressional analyses are given in Tables 4-3 and 4-5, and the predicted TSP values for each monitoring site are compared with the measured levels and annually adjusted levels in Tables 4-5 and 4-6, respectively.

TABLE 4-3

Summary Statistics for Regression Analysis Using Measured TSP Values

Variable	Coefficient	Std. Error	Significance
Area	.12144511E-02	.70736742E-03	2.9476579 .120
Point	.45607119E-02	.14556203E-02	9.8167807 .012
Local	47.323797	6.3333630	55.832929 .000
(Constant)	52.523894	3.8727563	183.93887

NOTE: Regressional degrees of Freedom = 3

Residual degress of Freedom = 9

TABLE 4-4

Summary Statistics for Regression Analysis Using Seasonally Adjusted TSP Values

Variable	Coefficient	Std. Error	Significance
Area	.49729543E-03	.65873682E-03	.56990840 .470
Point	.59115698E-02	.13555482E-02	19.018475 .002
Local	37.918263	5.8979524	41.332755 .000
(Constant)	44.353672	3.6065093	151.24541

NOTE: Regressional degrees of Freedom = 3

Residual degrees of Freedom = 9

TABLE 4-5

Microinventory Results Using Hamilton Specific Regression

Site	Microinventory Contribution ($\mu g/m^3$)				TSP (GEOM. MEAN) ($\mu g/m^3$)	
	Area	Point	Local	Sub Total	Predicted[a]	Measured[b]
Expt. 1	5	11	11	27	80	76
Expt. 2	7	11	17	35	88	84
Expt. 3	10	11	25	46	99	95
Expt. 4	10	11	7	28	81	80
Expt. 6	10	11	4	25	78	78
Control 1	4	10	13	27	80	82
Control 2	4	10	20	34	87	88
Control 3	6	10	29	45	98	99
John St.	8	9	29	46	99	109
Oak St.	7	11	41	59	112	105
School	2	21	0	23	76	77
Farm	1	0	0	1	54	59
Stelco Research Centre	1	< 1	0	1	54	47

[a] Calculated from regression of Hamilton microinventory microinventory data (Table 4-3): Geom. Av. TSP = $[0.00121(\text{AREA}) + 0.00456(\text{POINT}) + 47.3(\text{LOCAL}) - 52.5] \pm 5.4\ \mu g/m^3$

$(r = 0.9631,\ r^2 = 0.902)$

[b] Values measured during study period.

TABLE 4-6

Microinventory Results Using Annually Adjusted TSP Levels

Site	Microinventory Contribution ($\mu g/m^3$)				TSP (GEOM. MEAN) ($\mu g/m^3$)	
	Area	Point	Local	Sub Total	Predicted[a]	Measured[b]
Expt. 1	2	14	9	25	69	65
Expt. 2	3	14	14	31	75	71
Expt. 3	4	14	20	38	82	81
Expt. 4	4	14	6	24	68	68
Expt. 6	4	14	3	21	65	66
Control 1	2	13	11	26	70	70
Control 2	2	13	16	31	75	75
Control 3	3	13	23	39	83	84
John St.	3	12	23	38	82	93
Oak St.	3	14	33	50	94	89
School	1	27	0	28	72	75
Farm	< 1	0	0	< 1	44	50
Stelco Research Centre	1	< 1	0	1	45	40

[a] Calculated from regression of Hamilton Microinventory data (Table 4-4):

$$\text{TSP} = [0.000497(\text{AREA}) + 0.00591(\text{POINT}) + 37.9(\text{LOCAL}) + 44.35] \pm 5.04\ \mu g/m^3$$

$(r = 0.955,\ \text{adjusted } r^2 = 0.882)$

[b] Seasonally adjusted values

The standard deviations for these latter two calculations are quite similar (~ 5 μg/m^3) and, as would be anticipated, the correlation coefficients indicate an improvement in the fit of the data compared to the results obtained using the more general terms derived by Pace (51), (Table 4-2). A more substantial contribution by POINT sources and a reduction in the AREA contribution are the major differences compared to the predictions made using the PACE regression equation. The significance of these and other aspects of the microinventory results, including an assessment of the statistical significance of the relationships derived above, will be discussed in Section 5.2.2.

4.2 TSP Measurements

Typical temporal variations of the TSP data are shown in Figure 4-1, using TSP levels during the month of July 1979 at Experimental 3, Control 3 and SRC sites as examples. As can be seen from Figure 4-1, the variation in TSP levels is very consistent from site to site, with high and low TSP values occurring at all sites simultaneously throughout the study. The effects of meteorology are illustrated in the changes in TSP levels indicated as A, B and C in Figure 4-1. In A, over the 24 hour period of June 30 to July 1, the TSP levels dropped dramatically. This decrease coincides with an extended interval of rainfall commencing during the 0600 - 1200 hour period of June 30th. Wind direction is an important parameter in determining TSP loadings in the Hamilton area. The effect of wind is seen in the changes at B and C, where substantial decreases from very high (> 200 μg/m^3) to much lower (< 100 μg/m^3) levels occurred due to a wind shift from NE (i.e., from the industrial area) to SW over approximately a 12 hour period. Also observable in Figure 4-1 is the diurnal variation in TSP, with higher levels occurring during the daytime hours. It can be seen that the background levels, represented by the SRC site, follow the general trends in variability, but at much lower levels.

The 6-hour and 12-hour data were averaged for each station and the geometric means, geometric standard deviations and number of values for the complete study period are presented in Table 4-7. The individual data are listed in Appendix D.

The data were subdivided according to meteorological regimes as defined in Section 3.8.2 and the geometric means and standard deviations for each subset

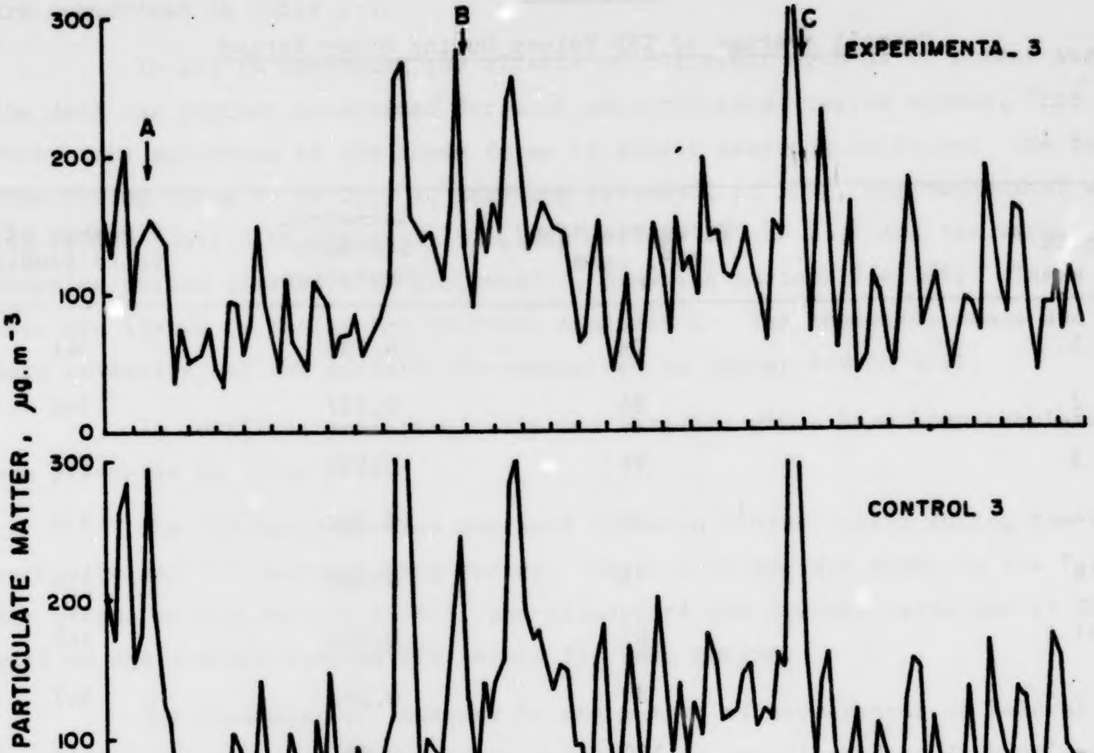


FIGURE 4-1 VARIATION OF TSP LEVELS DURING JULY 1979

TABLE 4-7

Overall Average of TSP Values During Study Period

Site	Geometric Mean TSP, μg/m^3	Geometric Standard Deviation	Number of Valid Samples
Expt. 1	78	0.533	341
2	84	0.537	348
3	96	0.535	342
4	80	0.543	332
6	78	0.542	328
Control 1	82	0.552	346
2	87	0.543	347
3	100	0.551	348
John St.	109	0.537	328
Oak Ave.	102	0.558	325
School	76	0.631	258
Farm	56	0.548	231
Stelco Research Centre	45	0.599	230

are summarized in Table 4-8.

To aid in assessing the effects of different methods of street sweeping, the data was further subdivided for each meteorological regime subset, into three sets according to the three forms of street sweeping activity; the baseline period (June 10 to July 7, sampling periods 1 to 109), the mechanical sweeping period (July 8 to August 7, sampling periods 110 to 233) and the vacuum sweeping period (August 8 to September 7, sampling periods 234-354). These subsets are listed in Tables D-5 to D-10, Appendix D. The geometric means and standard deviations of the subsets are summarized in Tables 4-9 to 4-11.

In addition, periods of calm and variable winds have been tabulated and are presented in Table 4-12.

The TSP data was also averaged for each 6-hour period during the day at each site and for each sweeping period. These averages are shown in the form of bar graphs in Figures 4-2 to 4-5, and illustrate the diurnal variation of TSP as well as the overall average TSP levels for each period.

One parameter of interest is the number of exceedences of Federal and Provincial criteria. However, these criteria are established as 24-hour and annual averages, whereas the study sampling periods were of 6 or 12-hour duration. The sweeping periods were of the order of one month, and the overall study was for three months. Thus, some method of calculating approximate "exceedence limits" for these averaging periods is required.

Various theoretical and empirical formulations of the effect of averaging (i.e. sampling) times have been developed to define the dependence of the ratio of concentrations to averaging time (237). Most show that the concentration ratio is given by power law function of time ratio as follows:

$$\frac{C_1}{C_o} = \left(\frac{t_1}{t_o}\right)^{-p}$$

where C_1 and C_o are the concentrations appropriate to averaging periods t_1 and t_o, respectively. P is a positive numerical exponent and, for the purpose of this study, can be evaulated using the Provincial daily and annual criteria for TSP of 120 and 60 $\mu g/m^3$ geometric means concentrations, respectively. This results in a value of P=0.1175. Plots of concentrations vs time for 24 hours and 1 year using

TABLE 4-8

Summary of Statistics for TSP as a Function of Meteorological Regimes

Station Regime	E1	E2	E3	E4	E6	C1	C2	C3	JS	OA	SC	F	ST
$r_1u_1p_1$	80 .504 5	79 .482 5	88 .421 5	67 .509 5	74 .410 5	68 .353 5	84 .398 5	74 .394 5	87 .363 5	73 .306 5	54 .314 4	50 .346 5	49 .474 5
$r_1u_1p_2$	67 .383 53	72 .367 54	83 .390 54	69 .430 53	66 .404 50	70 .403 54	73 .419 54	83 .365 54	90 .403 52	82 .382 53	89 .617 21	59 .387 20	41 .689 22
$r_1u_2p_1$	77 .489 14	78 .307 14	90 .308 14	81 .196 14	77 .183 14	69 .174 14	76 .174 14	91 .177 14	107 .202 14	92 .198 14	101 .218 15	54 .214 15	55 .151 14
$r_1u_2p_2$	68 .354 80	79 .349 80	90 .358 78	74 .374 72	70 .377 71	67 .348 81	73 .339 79	82 .414 81	97 .348 71	87 .357 71	122 .375 35	55 .381 34	49 .412 34
$r_1u_3p_1$	73 .081 6	94 .084 7	115 .086 7	83 .106 7	73 .101 7	67 .055 7	90 .010 6	93 .064 7	114 .088 7	106 .107 7	93 .091 5	29 .199 5	35 .186 5
$r_1u_3p_2$	86 .235 35	103 .247 35	122 .246 34	96 .233 30	89 .234 30	81 .182 35	88 .207 35	101 .238 35	136 .231 31	112 .197 30	108 .166 12	42 .296 13	45 .306 12
$r_2u_1p_1$	94 .107 14	99 .104 14	100 .107 14	90 .111 14	97 .116 14	112 .127 14	112 .133 14	117 .136 14	115 .119 14	122 .140 14	39 .142 8	71 .140 8	58 .074 8
$r_2u_1p_2$	102 .195 37	107 .175 38	118 .176 36	97 .195 38	97 .201 37	120 .195 38	133 .165 37	146 .175 38	135 .177 37	146 .195 37	53 .150 15	71 .146 15	47 .184 15
$r_2u_2p_1$	109 .027 2	118 .030 2	124 .036 2	108 .030 2	107 .028 2	125 .017 2	133 .015 2	151 .023 2	173 .017 2	152 .036 2	32 0 1	61 0 1	23 0 1
$r_2u_2p_2$	100 .241 45	99 .253 49	117 .233 49	95 .253 49	97 .255 47	120 .231 48	120 .249 48	144 .232 49	146 .243 49	147 .227 45	59 .250 28	72 .213 29	48 .251 39
$r_3u_1p_1$	73 .080 3	74 .080 3	77 .070 3	69 .080 3	71 .082 3	89 .082 3	90 .080 3	90 .081 3	80 .084 3	75 .012 3	39 .044 3	39 .009 2	39 .055 3
$r_3u_1p_2$	75 .099 17	77 .099 18	87 .103 18	72 .099 18	74 .109 18	86 .108 18	92 .122 17	100 .101 17	98 .092 17	97 .125 18	51 .084 8	57 .088 7	35 .084 8

NOTE: For each regime and site, three parameters are reported,

$\bar{x}$ = geometric mean TSP
S.D. = geometric standard deviation
n = number of events

Regime Definitions (Figure 3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = SW Sector	u_3 = > 18 km/hr	

TABLE 4-9

Summary Statistics for Baseline Period -TSP Subdivided by Meteorological Regime

Regime	E1	E2	E3	E4	E6	C1	C2	C3	JS	OA
$r_1u_1p_1$	72	75	86	57	69	67	66	71	85	66
	.828	.820	.653	.806	.671	.595	.604	.623	.537	.347
	2	2	2	2	2	2	2	2	2	2
$r_1u_1p_2$	60	61	65	56	50	59	45	66	73	73
	.313	.273	.245	.280	.296	.342	.420	.298	.317	.320
	7	7	7	6	6	7	7	7	6	6
$r_1u_2p_1$	74	84	95	79	69	65	70	86	95	94
	.323	.383	.390	.371	.321	.232	.229	.239	.305	.250
	3	3	3	3	3	3	3	3	3	3
$r_1u_2p_2$	58	71	78	62	54	56	61	65	79	72
	.434	.414	.445	.491	.438	.421	.402	.580	.429	.384
	30	29	30	20	19	29	27	28	20	19
$r_1u_3p_1$	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
$r_1u_3p_2$	91	105	116	99	89	85	88	98	133	115
	.342	.375	.374	.378	.372	.275	.326	.393	.382	.328
	19	19	19	14	14	19	19	19	15	14
$r_2u_1p_1$	132	143	140	125	143	184	186	204	180	217
	.070	.073	.070	.081	.055	.091	.091	.091	.076	.096
	4	4	4	4	4	4	4	4	4	4
$r_2u_1p_2$	92	100	111	91	81	113	137	132	117	132
	.150	.138	.140	.163	.198	.149	.124	.112	.146	.146
	9	10	10	10	10	10	10	10	10	10
$r_2u_2p_1$	146	164	182	149	144	151	156	193	207	221
	0	0	0	0	0	0	0	0	0	0
	1	1	1	1	1	1	1	1	1	1
$r_2u_2p_2$	129	86	113	94	88	128	119	148	139	174
	.183	.267	.207	.254	.244	.234	.235	.230	.241	.249
	8	10	10	10	10	9	10	10	10	10
$r_3u_1p_1$	146	152	153	129	126	187	183	187	160	215
	0	0	0	0	0	0	0	0	0	0
	1	1	1	1	1	1	1	1	1	1
$r_3u_1p_2$	51	59	58	54	54	73	61	81	62	79
	.092	.100	.082	.086	.095	.071	.061	.073	.105	.086
	4	4	4	4	4	4	4	4	4	4
$r_3u_2p_2$	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-

NOTE: For each regime and site, three parameters are reported,

$\bar{x}$ = geometric mean TSP

S.D. = geometric standard deviation

n = number of events

Regime Definitions (Figure 3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = SW Sector	u_3 = > 18 km/hr	

TABLE 4-10

Summary of Statistics for Mechanical Sweeping Period -TSP Subdivided by Meteorological Regime

Regime	E1	E2	E3	E4	E6	C1	C2	C3	JS	OA
$r_1u_1p_1$	129	134	136	100	111	102	101	111	124	85
	0	0	0	0	0	0	0	0	0	0
	1	1	1	1	1	1	1	1	1	1
$r_1u_1p_2$	73	80	92	78	79	77	82	91	104	89
	.201	.185	.188	.250	.205	.219	.186	.182	.189	.199
	28	29	29	28	28	29	29	29	27	29
$r_1u_2p_1$	74	80	96	78	77	69	74	86	104	83
	.072	.108	.109	.087	.073	.073	.071	.073	.101	.096
	8	8	8	8	8	8	8	8	8	8
$r_1u_2p_2$	87	96	114	97	96	88	94	105	120	107
	.142	.136	.127	.144	.146	.128	.126	.132	.143	.139
	24	25	23	25	25	25	25	25	25	25
$r_1u_3p_1$	97	117	144	125	109	78	89	117	150	133
	0	.003	.016	.007	.009	.002	.003	.002	.002	.001
	1	2	2	2	2	2	2	2	2	2
$r_1u_3p_2$	76	97	132	93	87	72	87	101	136	96
	.114	.119	.111	.118	.112	.078	.060	.062	.103	.076
	8	8	8	8	8	8	8	8	8	7
$r_2u_1p_1$	96	100	107	96	105	134	116	136	129	142
	.042	.037	.040	.041	.034	.023	.058	.038	.031	.039
	3	3	3	3	3	3	3	3	3	3
$r_2u_1p_2$	115	118	134	111	116	135	149	164	154	162
	.167	.148	.142	.166	.157	.162	.147	.147	.142	.165
	14	14	14	14	14	14	14	14	13	13
$r_2u_2p_2$	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
$r_2{}^4{}_2p_2$	97	105	126	100	101	110	119	132	144	135
	.141	.133	.131	.144	.131	.131	.138	.144	.161	.130
	18	18	18	18	17	18	17	18	18	17
$r_3u_1p_1$	34	37	43	36	39	41	40	41	41	35
	0	0	0	0	0	0	0	0	0	0
	1	1	1	1	1	1	1	1	1	1
$r_3u_1p_2$	54	55	82	53	57	59	60	71	79	63
	.055	.056	.077	.062	.065	.071	.070	.064	.050	.074
	6	6	6	6	6	6	5	5	5	6
$r_3u_2p_2$	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-

NOTE: For each regime and site, three parameters are reported,

$\bar{x}$ = geometric mean TSP
S.D. = geometric standard deviation
n = number of events

Regime Difinitions (Figure 3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = SW Sector	u_3 = > 18 km/hr	

TABLE 4-11

Summary of Statistics for Vacuum Sweeping Period
TSP Subdivided by Meteorological Regime

Regime	E1	E2	E3	E4	E6	C1	C2	C3	JS	OA
$r_1u_1p_1$	86 .038 3	82 .035 3	89 .037 3	76 .039 3	77 .033 3	69 .026 3	100 .018 3	75 .034 3	89 .035 3	78 .035 3
$r_1u_1p_2$	58 .090 14	62 .092 15	75 .112 15	58 .093 15	53 .088 15	59 .083 15	65 .096 15	71 .085 14	74 .115 15	68 .107 15
$r_1u_2p_1$	92 .038 3	68 .122 3	71 .127 3	92 .032 3	87 .043 3	75 .054 2	89 .050 3	110 .045 3	131 .039 3	115 .048 3
$r_1u_2p_2$	61 .145 22	69 .161 22	80 .153 21	63 .161 23	60 .165 23	59 .140 22	66 .150 23	77 .153 22	90 .157 21	75 .190 23
$r_1u_3p_1$	69 .060 5	86 .061 5	106 .061 5	71 .069 5	62 .064 5	63 .039 5	90 .008 4	85 .043 5	102 .061 5	96 .079 5
$r_1u_3p_2$	88 .063 8	107 .054 8	130 .051 7	94 .067 8	90 .082 8	79 .048 8	88 .059 8	110 .040 8	142 .065 8	124 .063 8
$r_2u_1p_1$	76 .059 7	80 .054 7	80 .059 7	73 .063 7	75 .067 7	73 .040 6	82 .055 7	80 .047 7	86 .055 7	83 .047 7
$r_2u_1p_2$	97 .089 14	102 .081 14	107 .082 12	89 .090 14	93 .086 13	112 .095 14	116 .064 13	139 .089 14	132 .081 14	142 .100 13
$r_2u_2p_1$	81 0 1	85 0 1	84 0 1	79 0 1	80 0 1	103 0 1	113 0 1	118 0 1	144 0 1	104 0 1
$r_2u_2p_2$	92 .178 19	101 .171 21	111 .168 21	93 .181 21	97 .192 20	125 .156 21	121 .179 21	154 .151 21	151 .161 21	145 .149 18
$r_3u_1p_1$	36 0 1	35 0 1	34 0 1	33 0 1	35 0 1	41 0 1	43 0 1	39 0 1	35 0 1	20 0 1
$r_3u_1p_2$	73 .064 8	73 .062 8	77 .061 8	66 .070 8	72 .077 8	87 .073 8	110 .076 8	97 .071 8	89 .054 8	105 .086 8
$r_3u_2p_2$	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -

NOTE: For each regime and site, three parameters are reported,

$\bar{x}$ = geometric mean TSP
S.D. = geometric standard deviation
n = number of events

Regime Difinitions (Figure 3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = SW Sector	u_3 = > 18 km/hr	

TABLE 4-12

Individual TSP Values ($\mu g/m^3$) for Variable & Calm Wind Conditions

Sampling Period	Wind Speed (km/hr)	E1	E2	E3	E4	E6	C1	C2	C3	JS	OA
		Variable									
33	2	113	92	102	103	96	155	131	142	147	148
41	8	201	216	208	201	147	205	175	234	249	216
111	4	59	60	66	56	47	61	74	89	67	84
117	10	157	150	158	151	150	204	213	219	179	213
124	17	219	231	272	223	211	198	218	243	225	282
139	7	134	135	143	126	141	142	140	148	143	138
143	5	97	110	121	104	106	106	116	143	136	139
191	8	79	91	96	80	93	93	100	117	133	112
199	7	142	166	191	144	154	117	137	169	239	165
271	9	123	136	148	107	106	123	64	144	199	155
277	1	116	119	119	106	112	143	82	147	156	145
281	2	105	104	106	96	99	109	149	113	116	114
282	0	70	69	75	65	70	81	108	84	91	80
	g.m.	116	120	129	112	111	126	115	146	152	144
	g.S.D. (ln)	0.167	0.174	0.175	0.173	0.167	0.159	0.168	0.145	0.165	0.156
		Calm									
62		69	73	70	69	66	74	127	115	84	94
94		63	71	78	53	55	74	72	73	101	84
198		60	64	72	58	63	73	75	82	80	73
286		74	71	82	70	71	113	126	114	104	113
314		73	78	76	68	69	74	78	76	86	89
330		80	80	79	74	74	100	98	101	84	99
	g.m.	70	73	74	65	66	83	[illegible]	92	91	92
	g.S.D. (ln)	0.0906	0.079	0.059	0.129	0.106	0.193	0.259	0.204	0.096	0.130

g.m. = geometric mean

g.S.D. (l_n) = geometic mean standard deviation (logarithmic)

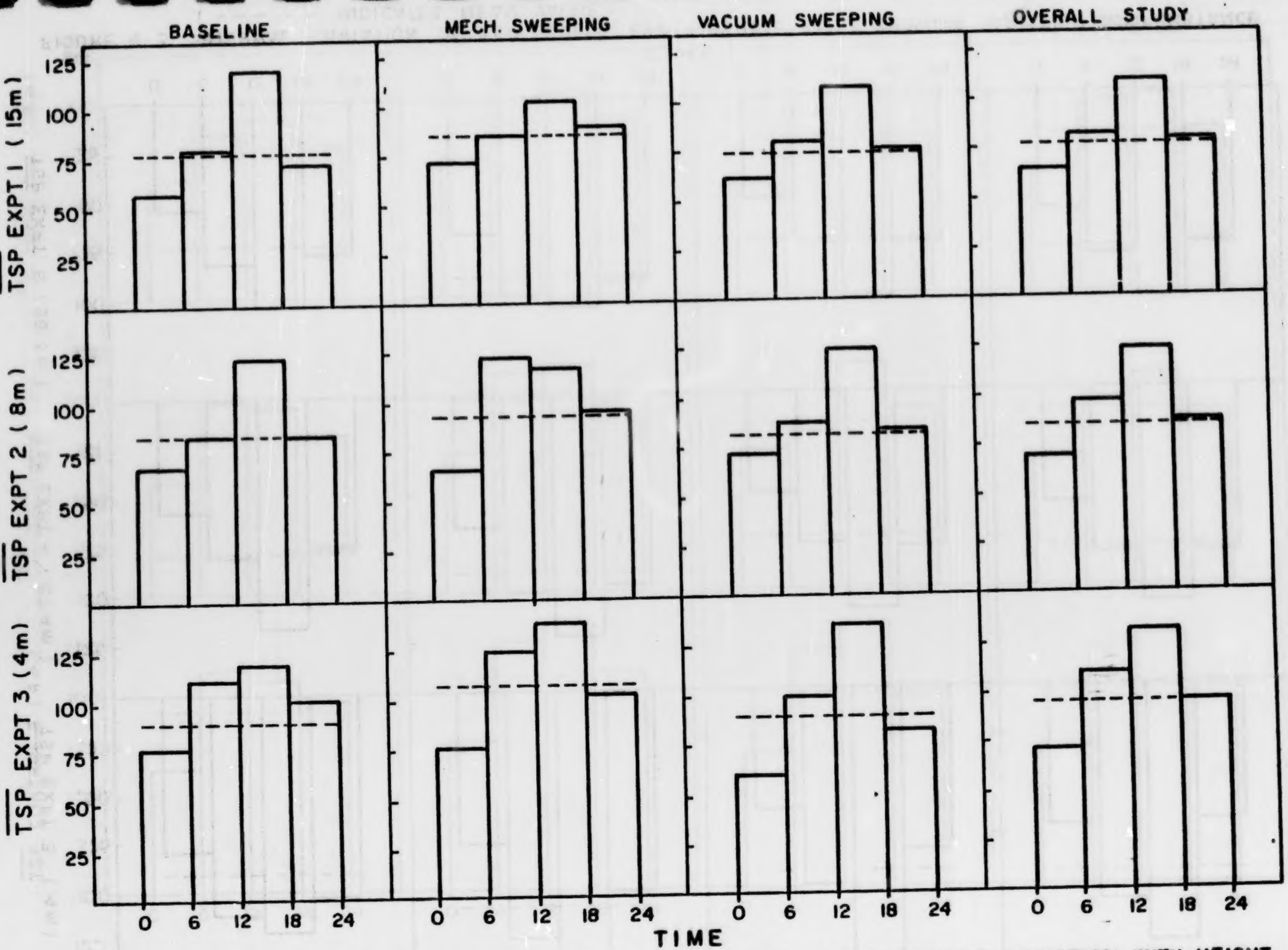


FIGURE 4-2 DIURNAL VARIATION OF TSP LEVELS, EXPERIMENTAL SITES SHOWING VARIATION WITH HEIGHT
(— — — — — INDICATES MEAN VALUE)

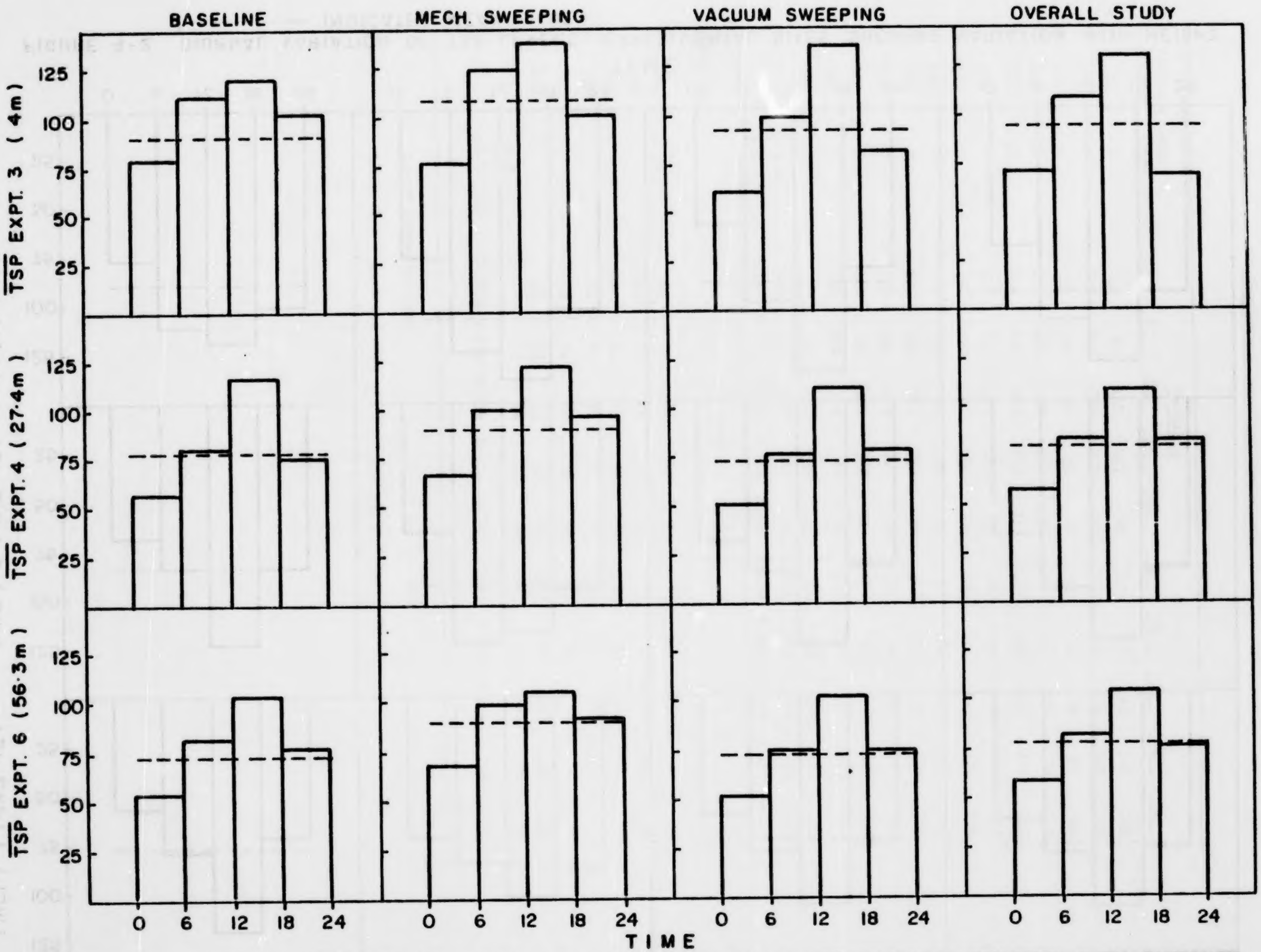


FIGURE 4-3 DIURNAL VARIATION OF TSP LEVELS, EXPERIMENTAL SITES SHOWING VARIATION WITH DISTANCE
(------ INDICATES MEAN VALUE)

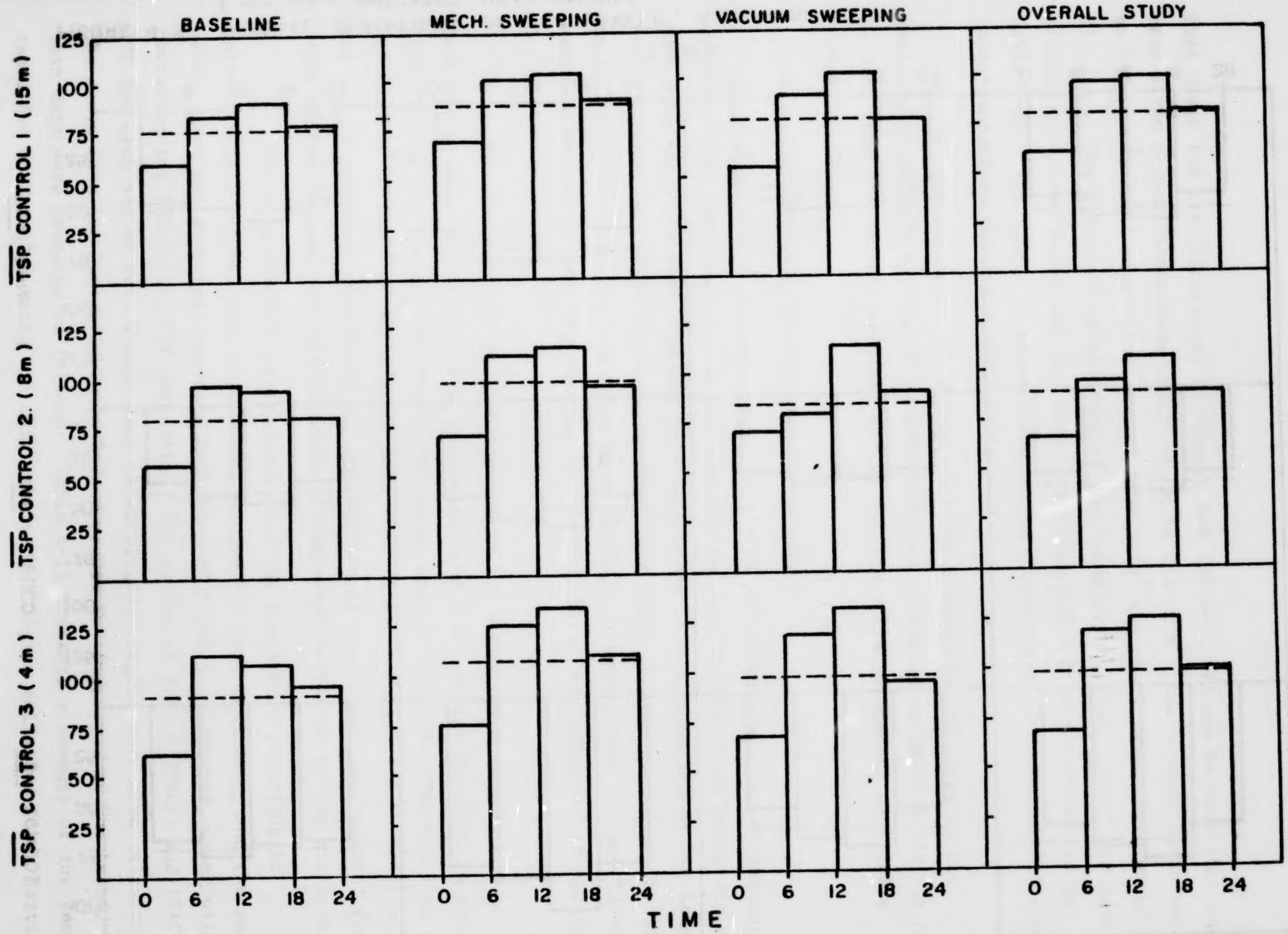


FIGURE 4-4 DIURNAL VARIATIONS OF TSP LEVELS, CONTROL SITE, SHOWING VARIATION WITH DISTANCE
(------ INDICATES MEAN VALUE)

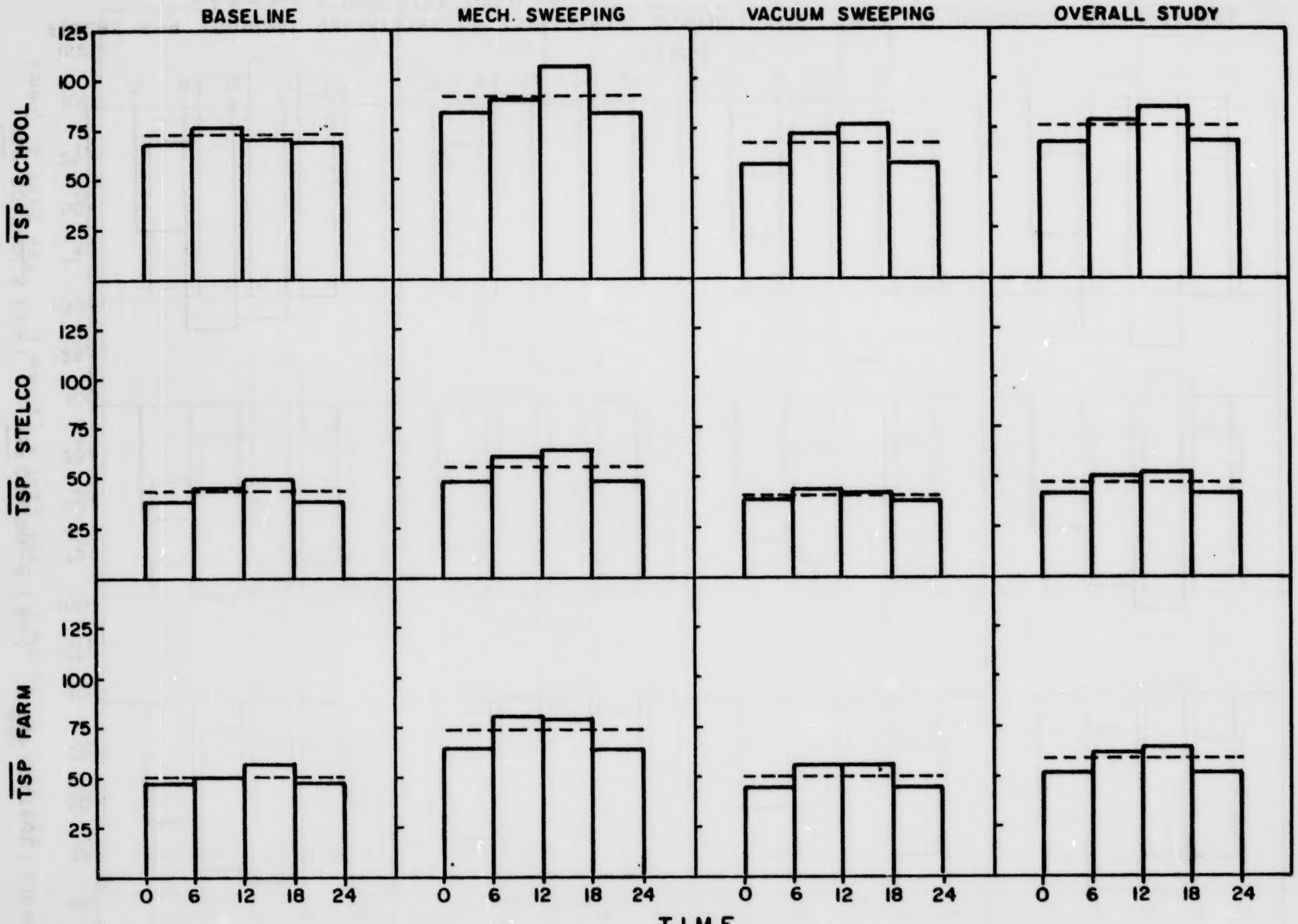


FIGURE 4-5 DIURNAL VARIATIONS OF TSP LEVELS, BACKGROUND SITES
(------ INDICATES MEAN VALUE)

this power law are illustrated in Figures 4-6 and 4-7. It can be seen that the equivalent 6-hour "exceedence limit" would be 141 $\mu g/m^3$, the 12-hour limit would be 130 $\mu g/m^3$, the 1 month limit would be 80 $\mu g/m^3$ and the 3 month limit would be 71 $\mu g/m^3$. The number of exceedences of the "equivalent 6-hour limit" for each station on Cannon Street and for each meteorological regime are presented in Table 4-13. The number of exceedences of the "equivalent 12-hour limit" for the background sites are included in Table 4-14.

A compilation of historical data for representative sites in the Hamilton study area for the years 1974-1979 are presented in Table 4-15. It can be seen that the results obtained during the study are consistent with these historical data.

4.3 Size-Specific Particulate Measurements

Fine (< 2.5 μm) and coarse (2.5 - 15 μm) particulate matter ambient concentrations were measured at the Experimental and Control Sites using dichotomous samplers. The mass loadings were determined by β-attenuation of the sample filters before and after exposure, as described above (Section 3.8.3). The detailed results of the β-attenuation mass loadings determinations for the 12-hour sampling periods at the Experimental and Control sites are tabulated in Appendix E.

The basis of the cut-points used in the dichotomous sampler has been reviewed in Section 2.1.1, and as discussed, the < 15 μm size fraction is obtained from the sum of fine (F) and coarse (C) measurements, (F + C). The < 2.5 μm is referred to as the fine particulate mass (F). Also, as discussed in Section 2.1.1, the 2.5 μm cut-point represents the demaraction of the "fine" and "coarse" fractions of the typical size distribution of suspended particles in the atmosphere.

The size-specific particulate data was subdivided according to meteorological regime, in a similar way to the TSP data treatment, and the geometric mean and geometric standard deviation of F and C calculated, along with the corresponding TSP value, for each site. The ratios of F/C, F/(F+C), and (F+C)/TSP for each set of data within each meteorologcial regime were also calculated. The above data are listed in Table E-3, Appendix E. Summaries of the geometric mean data were prepared as follows: Table 4-16 presents a summary of the geometric means for each regime using all data within that regime collected for a particular

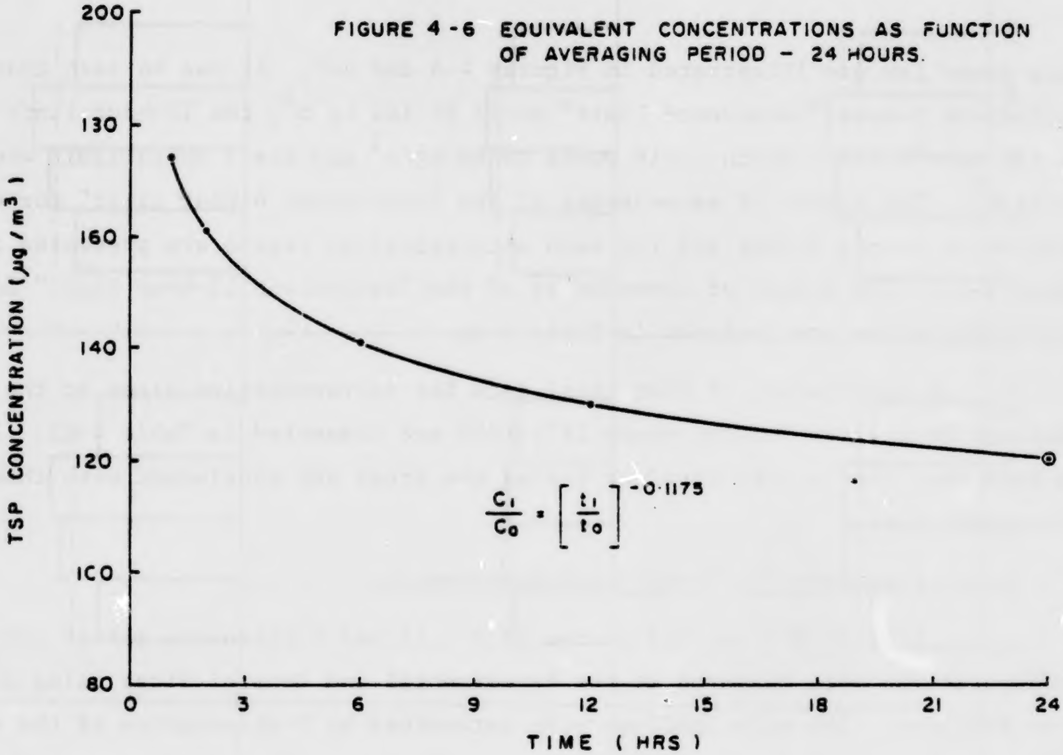


FIGURE 4-6 EQUIVALENT CONCENTRATIONS AS FUNCTION OF AVERAGING PERIOD - 24 HOURS.

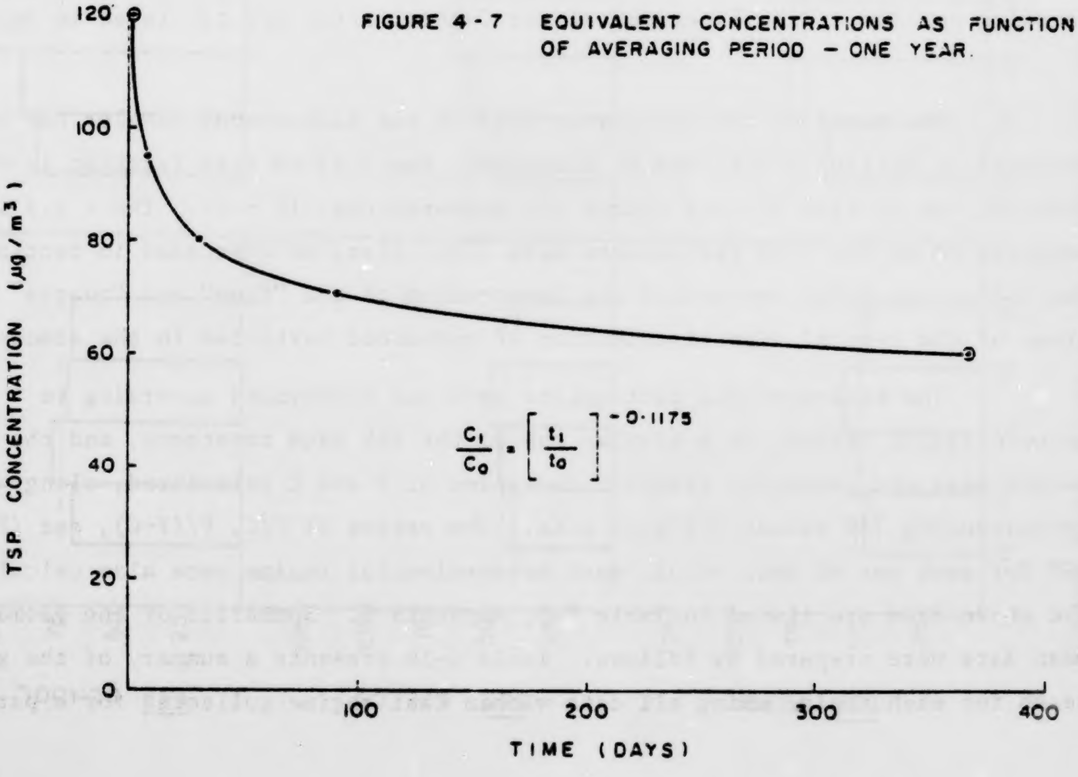


FIGURE 4-7 EQUIVALENT CONCENTRATIONS AS FUNCTION OF AVERAGING PERIOD - ONE YEAR.

TABLE 4-13

Exceedences* of "Equivalent 6-hour" Criteria** for Cannon St. Sites as a Function of Meteorological Regime

Regime	G1	E2	E3	E4	E6	C1	C2	C3	JS	OA	TOTAL
$r_1u_1p_1$	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/50
$r_1u_1p_2$	1/49	1/51	5/51	1/49	3/48	2/51	4/51	6/49	8/48	2/50	33/497
$r_1u_2p_1$	1/14	2/14	4/14	1/14	1/14	0/13	0/14	1/14	4/14	2/14	16/139
$r_1u_2p_2$	3/76	5/76	15/72	5/68	4/67	2/76	4/75	6/75	17/66	11/67	72/718
$r_1u_3p_1$	0/6	1/7	2/7	0/7	0/7	0/7	0/6	0/7	4/7	2/7	7/68
$r_1u_3p_2$	7/35	11/35	14/34	8/30	6/30	3/35	5/35	11/35	16/31	11/29	92/329
$r_2u_1p_1$	2/14	3/14	4/14	1/14	2/14	4/13	4/14	5/14	5/14	6/14	36/139
$r_2u_1p_2$	7/37	8/38	10/36	6/38	5/37	14/38	16/37	19/38	19/37	22/36	126/372
$r_2u_2p_1$	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	2/2	1/2	11/20
$r_2u_2p_2$	11/45	14/49	18/49	10/49	11/47	19/48	20/48	27/49	26/48	25/45	181/478
$r_3u_1p_1$	1/3	1/3	1/3	0/3	0/3	1/3	1/3	1/3	1/3	1/3	8/30
$r_3u_1p_2$	0/17	0/18	1/18	0/18	0/18	1/18	2/17	1/17	0/17	3/18	8/176
TOTAL:	34/303	47/312	75/305	33/297	33/292	48/309	57/307	78/308	100/293	85/290	590/3016

* Listed as exceedences per number of events. (i.e., for $r_1u_1p_1$ at E1, 0/5 indicates 0 exceedences in 5 events.

** "Equivalent 6-hour" criteria is 142 $\mu g/m^3$

Regime Definitions (Figure 3-24)

Wind Dir	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = NW Sector	u_3 = > 18 km/hr	

TABLE 4-14

Exceedences* of "Equivalent 12-hour" Criterion** for Background Sites as a Function of Meteorological Regime

Regime	School	Farm	SRC	Total
$r_1u_1p_1$	0/3	0/4	0/4	0/11
$r_1u_1p_2$	5/20	1/19	0/22	6/61
$r_1u_2p_1$	5/15	0/15	0/14	5/44
$r_1u_2p_2$	16/32	0/32	0/31	16/95
$r_2u_2p_1$	1/5	0/5	0/5	1/15
$r_1u_3p_2$	4/12	0/13	2/12	6/37
$r_2u_1p_1$	0/8	1/8	0/7	1/23
$r_2u_1p_2$	0/15	1/15	0/15	1/45
$r_2u_2p_1$	0/1	0/1	0/1	0/3
$r_2u_2p_1$	1/28	2/29	0/30	3/87
$r_3u_1p_1$	0/3	0/2	0/3	0/8
$r_3u_1p_2$	0/8	0/7	0/8	0/23
TOTAL:	32/150	5/150	2/152	39/452

---

* Listed as exceedences per number of events. (i.e., for $r_1u_1p_1$ at School Site, 0/3 = 0 exceedences in 3 events.

** "Equivalent 12 hour" criterion is 130 $\mu g/m^3$.

Regime Definitions (Figure 3-24)

Wind Dir	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = NW Sector	u_3 = > 18 km/hr	

TABLE 4-15

Prevailing TSP Levels in the Hamilton Area

Location	Geometric Means 1976	1977	1978
City Hall*			
June	131	60	83
July	73	70	95
August	74	35	83
September	89	40	65
Annual	65	54	61
Hughson/Hunter**			
June	145	67	75
July	80	74	92
August	73	44	95
September	105	52	72
Annual	76	63	64
Hughson St. N.***			
June	124	62	127
July	66	68	79
August	96	45	79
September	102	42	68
Annual	60	59	63

* S of the Experimental Site

** SE of the Experimental Site

*** NE of Experimental Site

(all sites within 0.5 km of Experimental Site)

TABLE 4-16

Dichotomous Sampler Results: Average of all Values for Meteorological Regimes

(loadings in $\mu g/m^3$)

Regime	EXPERIMENTAL TSP	F	C	$\frac{F}{C}$	$\frac{F}{(F+C)}$	$\frac{(F+C)}{TSP}$	CONTROL TSP	F	C	$\frac{F}{C}$	$\frac{F}{(F+C)}$	$\frac{(F+C)}{TSP}$
$r_1u_1P_1$ (4,2)	81	20.8	19.4	1.07	0.52	0.50	74	12.7	17.2	0.74	0.42	0.40
$r_1u_1P_2$ (20,12)	90	18.9	21.2	0.89	0.47	0.45	99	22.7	27.7	0.82	0.45	0.51
$r_1u_2P_1$ (10,8)	80	22.9	15.5	1.48	0.60	0.48	85	24.4	20.2	1.21	0.55	0.52
$r_1u_2P_2$ (28,15)	99	20.6	24.1	0.85	0.46	0.45	99	22.2	22.3	1.00	0.50	0.45
$r_1u_3P_1$ (3,2)	86	10.6	23.4	0.45	0.31	0.40	107	27.7	30.0	0.92	0.48	0.54
$r_1u_3P_2$ (5,4)	105	15.0	22.9	0.66	0.40	0.36	92	16.7	28.5	0.59	0.37	0.49
$r_2u_1P_1$ (7,4)	114	34.3	20.0	1.72	0.63	0.48	154	49.5	39.0	1.27	0.56	0.57
$r_2u_1P_2$ (10,3)	109	24.7	24.1	1.02	0.51	0.45	122	30.1	33.0	0.91	0.48	0.52
$r_2u_2P_2$ (14,8)	121	27.0	32.0	0.84	0.46	0.49	147	30.1	44.5	0.68	0.40	0.51
$r_2u_2P_1$ (1,0)	72	15.1	14.1	1.07	0.52	0.40	93	-	-	-	-	-
$r_3u_1P_1$ (3,1)	49	13.2	11.5	1.15	0.53	0.50	62	6.6	15.0	0.44	0.31	0.35
$r_3u_2P_1$ (1,1)	147	49.1	29.6	1.66	0.62	0.54	234	95.6	59.4	1.61	0.62	0.66
$r_3u_2P_2$ (5,3)	76	12.1	19.6	0.62	0.38	0.42	76	7.6	28.0	0.27	0.21	0.47
$r_3u_1P_2$ (4,3)	79	13.7	14.1	0.97	0.49	0.35	70	6.0	12.6	0.48	0.32	0.27
Variable (2,0)	99	25.2	20.3	1.24	0.55	0.46	107	-	-	-	-	-
Overall (117, 64)	95	20.7	21.8	0.95	0.49	0.45	118	24.0	29.3	0.82	0.45	0.45

NOTE: Numbers in brackets following regime designation refer to number of values available for Experimental and Control Sites, respectively.

Regime Definitions (Figure 3-24)

Wind Dir	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	P_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	P_2 = none
r_3 = NW Sector	u_3 = > 18 km/hr	

site with corresponding ratios. Table 4-17 contains the average means and ratios calculated for each regime parameter using the data from Table 4-17. Table 4-18 presents a summary of the geometric means for each regime calculated using data collected within the regime for periods when data for both sites are available (i.e. no missing data at either site). Table 4-19 contains the means and ratios calcualted for each regime parameter using the data from Table 4-18. The loss of data between Table 4-16 and 4-18 is due to sampler malfunctions in the field. The means and ratios calculated for each regime parameter were obtained in order to make more meaningful interpretations for those conditions where a regime contains very few events. There is insufficient size-specific data to allow subdivision according to the three periods of different road-sweeping methodologies.

4.4 Meteorological Data

Meteorological data were obtained from five sites in the study area. Data were collected on wind speed (WS), wind direction (WD), precipitation (P) and ambient temperature. The five sites used were:

i) Experimental Site, 7 m tower recording WS, WD

ii) Control Site, 8 m tower recording WS, WD

iii) Mount Hope Airport, 10 m tower (AES station), recording WS, WD

iv) Royal Botanical Gardens, 10 m tower (AES station, recording WS, WD

v) MOE/Woodward St. tower, WS, WD and T at 21 m (top) and 61 M (200 ft.).

Hourly precipitation data also were obtained from the AES station at the Royal Botanical Gardens and are listed for the study period in Table F1 to F4, Appendix F.

The hourly wind speed and direction for all five stations for the study period (June - September 1979) are tabulated in Appendix F. For the purposes of interpreting meteorological factors during the study, the data for MOE Woodward St. was chosen as most representative of the study area. Six and twelve hour averages of wind speed and direction from Woodward St. and 6 and 12-hour accumulations of precipitation from the Royal Botanical Gardens are listed with the TSP data in

TABLE 4-17

Dichotomous Sampler Results - Averaged for
each Regime Parameter
(loadings in $\mu g/m^3$)

Regime Parameter	EXPERIMENTAL TSP	EXPERIMENTAL F	EXPERIMENTAL C	EXPERIMENTAL $\frac{F}{C}$	EXPERIMENTAL $\frac{F}{(F+C)}$	EXPERIMENTAL $\frac{(F+C)}{TSP}$	CONTROL TSP	CONTROL F	CONTROL C	CONTROL $\frac{F}{C}$	CONTROL $\frac{F}{(F+C)}$	CONTROL $\frac{(F+C)}{TSP}$
r_1 av. (70,43)	92	19.4	21.4	0.91	0.48	0.44	95	21.8	23.8	0.92	0.48	0.48
r_2 av. (32,15)	114	27.1	25.8	1.05	0.51	0.46	143	34.4	40.5	0.85	0.46	0.52
r_3 av. (13, 8)	73	14.3	16.2	0.88	0.47	0.42	83	9.4	21.1	0.45	0.31	0.37
u_1 av. (48,25)	92	20.9	19.9	1.05	0.51	0.44	100	20.6	25.5	0.81	0.45	0.46
u_2 av. (59,35)	96	21.6	23.4	0.92	0.48	0.46	105	23.1	26.8	0.86	0.46	0.48
u_3 av. (8, 6)	97	13.2	23.1	0.57	0.36	0.37	97	19.8	29.0	0.68	0.41	0.50
p_1 av. (29,18)	85	22.0	17.5	1.26	0.56	0.46	102	27.0	25.1	1.08	0.52	0.51
p_2 av. (86,48)	99	20.1	23.5	0.86	0.46	0.44	102	20.1	27.0	0.74	0.43	0.46
Overall	95	20.7	21.8	0.95	0.49	0.45	118	24.0	29.3	0.82	0.45	0.45

NOTE: Numbers in brackets following regime designation refer to number of values available for Experimental and Control Sites, respectively

Regime Definitions (Figure 3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = NW Sector	u_3 = > 18 km/hr	

4-1

Dichotomous Sampler Results - Average of Paired Values
for Meteorological Regimes
(loadings in µg/m^3)

Regime		EXPERIMENTAL						CONTROL					
		TSP	F	C	$\frac{F}{C}$	$\frac{F}{(F+C)}$	$\frac{(F+C)}{TSP}$	TSP	F	C	$\frac{F}{C}$	$\frac{F}{(F+C)}$	$\frac{(F+C)}{TSP}$
$r_1u_1p_1$	(1)	51	11.8	13.9	0.85	0.46	0.50	46	4.6	12.9	0.36	0.26	0.38
$r_1u_1p_2$	(10)	88	20.5	22.4	0.92	0.48	0.49	93	20.0	25.4	0.79	0.44	0.49
$r_1u_2p_1$	(6)	86	22.6	16.0	1.41	0.59	0.45	79	24.5	17.5	1.40	0.58	0.53
$r_1u_2p_2$	(15)	101	20.4	25.0	0.82	0.45	0.45	99	22.2	22.3	1.00	0.50	0.45
$r_1u_3p_1$	(1)	108	18.2	23.9	0.76	0.43	0.40	93	25.5	21.1	1.21	0.55	0.50
$r_1u_3p_2$	(4)	111	16.2	25.7	0.63	0.39	0.38	92	16.7	28.5	0.59	0.37	0.49
$r_2u_1p_1$	(4)	121	35.9	18.8	1.91	0.66	0.45	154	49.5	39.0	1.27	0.56	0.57
$r_2u_1p_2$	(3)	96	21.2	22.8	0.93	0.48	0.46	122	30.1	33.0	0.91	0.48	0.52
$r_2u_2p_2$	(5)	122	29.6	35.8	0.83	0.45	0.54	167	32.9	44.5	0.74	0.43	0.46
$r_3u_1p_1$	(1)	48	9.2	14.1	0.65	0.39	0.49	62	6.6	15.0	0.44	0.31	0.35
$r_3u_1p_2$	(2)	68	10.3	10.3	1.00	0.5	0.30	52	6.0	11.0	0.55	0.35	0.33
$r_3u_2p_1$	(1)	147	49.1	29.6	1.66	0.62	0.54	234	95.6	59.4	1.61	0.62	0.66
$r_3u_2p_2$	(3)	79	11.0	21.1	0.52	0.34	0.41	76	7.6	28.0	0.27	0.21	0.47
Overall	(56)	91	18.0	15.8	1.14	0.53	0.37	97	19.4	25.3	0.77	0.43	0.46

NOTE: Numbers in brackets following regime designation refer to number of values available for Experimental and Control Sites, respectively.

Regime Definitions Figure (3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = NW Sector	u_3 = > 18 km/hr	

TABLE 4-19

Dichotomous Sampler Results - Average of Paired Values for Each Regime Parameter (loadings in $\mu g/m^3$)

Regime Parameter	EXPERIMENTAL TSP	F	C	$\frac{F}{C}$	$\frac{F}{(F+C)}$	$\frac{(F+C)}{TSP}$	CONTROL TSP	F	C	$\frac{F}{C}$	$\frac{F}{(F+C)}$	$\frac{(F+C)}{TSP}$
r_1 av. (37)	94	19.9	22.3	0.89	0.47	0.45	91	20.4	22.4	0.91	0.48	0.47
r_2 av. (12)	115	29.0	25.8	1.12	0.68	0.48	150	36.9	39.5	0.93	0.48	0.51
r_3 av. (7)	77	13.0	17.0	0.76	0.43	0.39	78	10.0	14.6	0.68	0.41	0.32
u_1 av. (21)	87	20.1	19.3	1.04	0.51	0.45	72	19.9	24.9	0.80	0.44	0.62
u_2 av. (30)	100	21.4	24.0	0.89	0.47	0.46	103	22.8	17.4	1.31	0.57	0.39
u_3 av. (5)	110	16.6	25.3	0.66	0.40	0.38	92	18.2	26.8	0.68	0.40	0.49
P_1 av. (14)	93	24.0	17.7	1.36	0.58	0.45	99	26.8	23.5	1.14	0.53	0.51
P_2 av. (42)	83	19.4	24.0	0.81	0.45	0.52	100	19.6	25.8	0.76	0.43	0.46
Overall (56)	96	20.5	22.2	0.92	0.48	0.44	99	21.2	25.2	0.84	0.45	0.47

NOTE: Numbers in brackets refer to the numbers of paired observations for each regime parameter.

Regime Definitions Figure (3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	P_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	P_2 = none
r_3 = NW Sector	u_3 = > 18 km/hr	

Appendix D, Tables D1 and D2. Frequencies of wind speed and direction are summarized in Figures 4-8 to 4-10 for the 21 m and 61 m monitors at the Woodward St. MOE station. These data are presented as wind roses for the overall study period, the mechanical sweeping period and the vacuum sweeping period, respectively.

4.5 Chemical Analysis

A summary of the chemical analyses performed on selected filters is presented in Figure 3-5. The results of these analyses are tabulated in Appendix G, as follows:

- XRF analyses of dichotomous filters - Table G-1
- IC and AA analyses of glass-fibre and cellulose filters - Tables G-2.1 to G-2.6 and G-3.1 to G-3.8
- NAA analyses of cellulose filters - Tables G-4.1 and G-4-2
- Morphological analyses of the selected subset of glass-fibre filters - Tables G-6.1 and G-6.2
- Carbon analyses on selected Filters - Table H series.

Using results from IC and AA analyses of the glass-fibre filters, Pearson correlation coefficients were calculated between each parameter analyzed for each site. These results are summarized and discussed in Section 5.1.

Averages of data for the meteorological regimes were obtained for the parameters SO_4^{2-}, NO_3^-, Mn, Cu, Fe, Pb and Ni. These parameters were chosen because significant concentrations were found for each filter analyzed. The calculated averages are summarized in Appendix K-2.

Pearson correlation coefficients were calculated as above for the data obtained from NAA of the cellulose filters used in the tracer experiment. These calculations are summarized and discussed in Section 5.1. The coefficients are calculated for each consecutive period after a tracer application up to the third period after application (i.e. Tracer applied during 0600 - 1200 hrs. period, correlation coefficients calculated for data in periods 1200 - 1800 hrs., 1800 - 2400 hrs., and 0000 - 0600 hrs. following application).

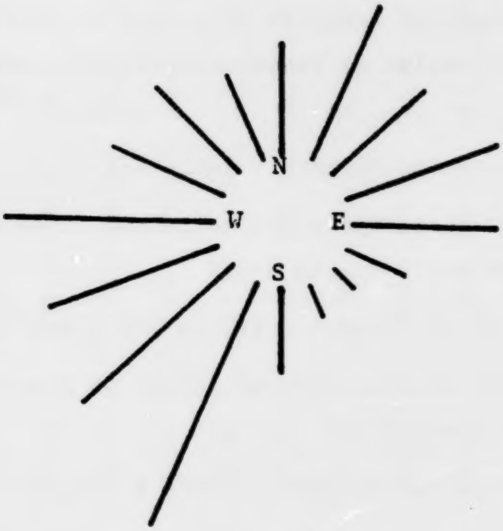
4.6 Other Parameters

Data obtained on CO levels, CO and traffic counts are listed in

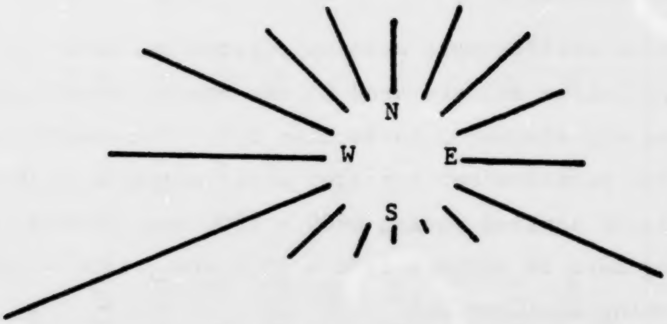
FIGURE 4-8

Wind Frequency Distribution

Woodward Street



Level I (10 m) - Entire Study Period



Level II (61 M) - Entire Study Period

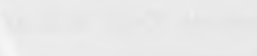


Figure 4-9

Wind Frequency Distribution

Woodward Street - Level I (10 m)

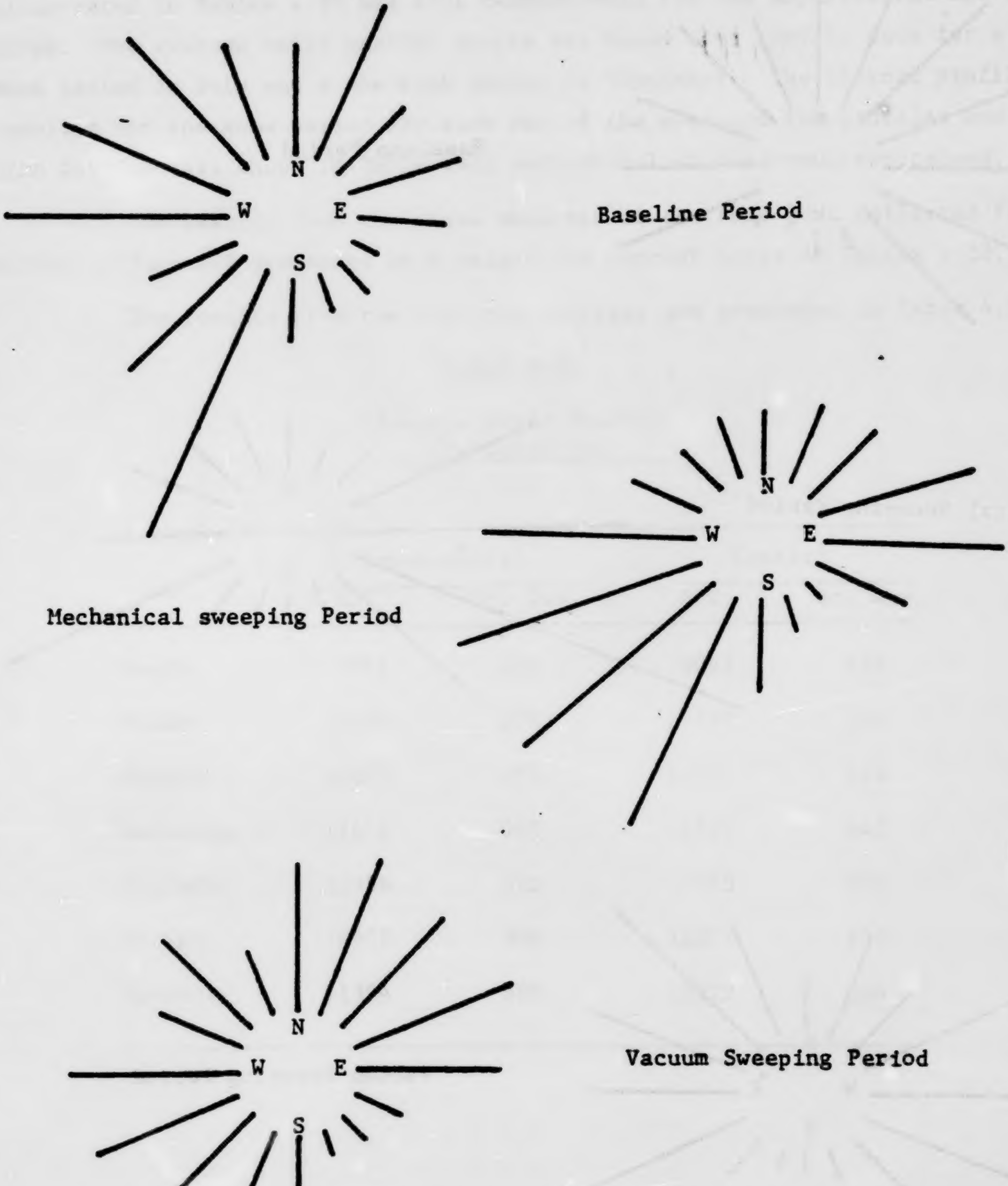
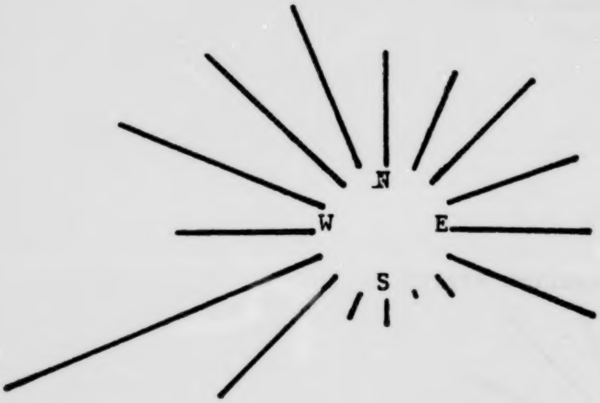


Figure 4-10

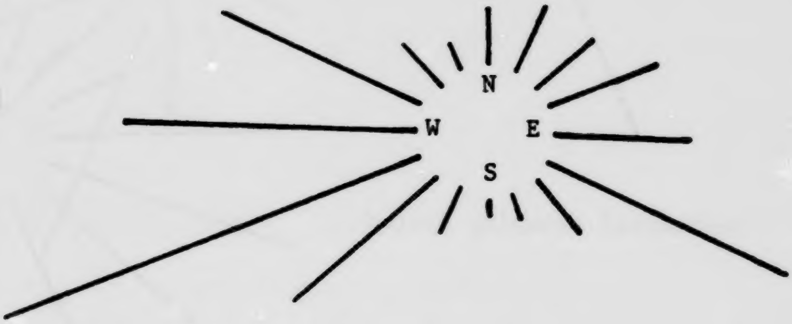
Wind Frequency Distribution

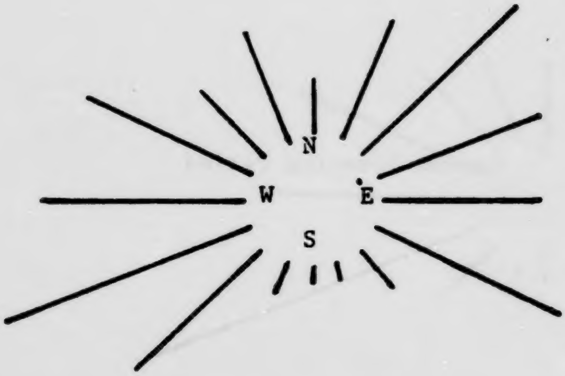
Woodward Street - Level II (61 m)



Baseline Period

Mechanical Sweeping Period





Vacuum Sweeping Period

0 5% 10%

Appendix H, Tables H-1 to H-3. Average daily and dirunal traffic variations are illustrated in Tables 4-20 and 4-21 respectively for the Experimental and Control Sites. The average daily traffic counts are based upon traffic data for a four week period in July and a one week period in September. The diurnal profiles were complied for the same period for each day of the week and the profiles and variation for Tuesdays shown in Table 4-21 and typical of the results obtained.

The results from the sieve analysis of the road dust collected from the street surface are presented on a weight and percent basis in Tables 4-22, 4-23.

The results from the dustfall analyses are presented in Table 4.24.

TABLE 4-20

Average Daily Traffic
(Vehicles/Day)

Day	Experimental		Control	
	ADT	St. Dev.	ADT	St. Dev.
Sunday	7941	225	8092	428
Monday	14655	277	15799	361
Tuesday	15872	292	16655	678
Wednesday	15672	580	16581	840
Thursday	16358	320	17528	601
Friday	16955	399	18257	853
Saturday	11394	609	12222	504

TABLE 4-21

Typical Diurnal Traffic Pattern*

Period	Experimental		Control	
(hrs.)	Traffic	Std. Dev.	Traffic	Std. Dev.
0000-0200	307	40	158	66
0200-0400	128	32	40	10
0400-0600	199	25	168	64
0600-0800	1538	312	1564	177
0800-1000	1594	196	1630	221
1000-1200	1655	61	1732	48
1200-1400	1797	52	1882	111
1400-1600	2194	113	2429	100
1600-1800	3456	314	3200	254
1800-2000	1413	89	1340	62
2000-2200	885	59	859	67
2200-2400	729	24	799	35

* Based on Tuesday data

Traffic count on vehicles/2-hour period

TABLE 4-22

Road Dust Samples

Weight (g)

Site	Date			North Side			South Side			Combined		
	D	M	Y	>20 mesh	>400 mesh	<400 mesh	>20 mesh	>400 mesh	<400 mesh	>20 mesh	>400 mesh	<400 mesh
Experimental	4	7	79	122.5	341.1	21.3	118.7	324.0	24.3	241.2	665.1	45.6
	20	8	79	66.2	230.6	14.9	99.3	192.6	9.3	165.5	423.2	24.2
	6	9	79	213.5	482.7	15.2	150.3	342.7	14.0	383.8	825.4	29.2
	17	7	79							86.5*	451.1*	20.9*
Control	5	7	79	36.0	149.0	9.2	91.7	254.3	24.9	127.7	403.3	34.1
	18	7	79	46.0	373.2	32.6	34.3	171.6	17.8	80.3	544.8	50.4
	8	8	79	222.6	464.0	20.9	358.2	606.1	39.2	580.8	1070.1	60.1
	27	8	79	550.6	790.3	19.9	173.2	393.1	24.0	723.8	1182.4	43.9
	6	9	79	467.0	914.3	20.3	533.9	892.4	22.4	1000.9	1806.7	42.7
John	7	7	79	73.1	175.9	7.2	73.7	175.4	10.0	146.8	351.3	17.2
	25	7	79	184.8	301.4	4.4	142.6	208.7	2.9	327.4	510.1	7.3
	23	8	79	97.5	289.2	17.8	215.6	447.7	23.6	313.1	736.9	41.4
	7	9	79	227.4	589.5	16.0	208.0	483.4	25.0	435.4	1072.9	41.0
Oak	6	7	79	61.3	171.2	10.2	50.0	121.0	6.6	111.3	292.2	15.8
	23	7	79	163.3	285.6	7.7	269.4	1042.2	40.3	432.7	1327.8	48.0
	22	8	79	467.5	1080.3	19.4	264.7	461.2	43.5	732.2	1541.5	95.9
	5	9	79	473.0	1036.1	19.5	200.5	454.2	19.3	673.5	1490.5	38.8

* = Combined sample only

20 mesh = 841μ
400 mesh = 37μ

TABLE 4-23

Road Dust Samples

(percent weight)

Site	Date			North Side			South Side			Combined		
	D	M	Y	>20 mesh	>400 mesh	<400 mesh	>20 mesh	>400 mesh	<400 mesh	>20 mesh	>400 mesh	<400 mesh
Experimental	4	7	79	33.8	94.1	5.9	34.1	93.0	7.0	33.9	93.6	6.4
	20	8	79	27.0	93.9	6.1	49.2	95.4	4.6	37.0	94.6	5.4
	6	9	79	42.9	96.9	3.1	42.1	96.1	3.9	42.6	96.8	3.4
	17	7	79							86.5*	18.3*	4.4*
Control	5	7	79	22.8	94.2	5.8	32.8	91.1	8.9	29.2	92.2	7.8
	18	7	79	11.3	92.0	8.0	18.1	90.6	9.4	13.5	91.5	8.5
	8	8	79	45.9	95.7	4.3	55.5	93.9	6.1	51.4	94.7	5.3
	27	8	79	68.0	97.5	2.5	41.6	94.2	5.8	59.0	96.4	3.6
	6	9	79	50.0	97.8	2.2	58.4	97.6	2.4	54.1	97.7	2.3
John	7	7	79	39.9	96.1	3.9	39.8	94.6	5.4	39.8	95.3	4.7
	25	7	79	60.4	98.6	1.4	67.4	98.6	1.4	63.3	98.6	1.4
	23	8	79	31.8	94.2	5.8	45.7	95.0	5.0	40.2	94.7	5.3
	7	9	79	37.5	97.4	2.6	40.9	95.1	4.9	39.1	96.3	3.7
Oak	6	7	79	33.8	94.4	5.6	34.2	94.8	5.2	36.0	94.6	5.4
	23	7	79	55.7	97.4	2.6	24.9	96.3	3.7	31.5	96.5	3.5
	22	8	79	42.5	98.2	1.8	52.4	91.2	8.6	44.7	94.1	5.9
	5	9	79	44.8	98.2	1.8	42.3	95.9	4.1	44.0	97.5	2.5

* = Combined sample only
20 mesh = 841μ
400 mesh = 37μ

TABLE 4-24

Analysis of Dustfall
(g/m^2/30 days)

Period		Dustfall	Fe	Ca	Pb	Mn	Zn	Al
July 10 - Aug. 10	Expt.	8.1	0.337	0.346	0.011	0.020	0.019	0.057
	Control	8.5	0.425	0.394	0.015	0.037	0.037	0.059
Aug. 10 - Sept. 7	Expt.	4.9	0.355	-	0.007	0.036	0.019	0.400
	Control	4.6	0.314	-	0.007	0.019	0.012	0.310

4.7 Chemical Element Balance Results

The CMB calculations were carried out on 53 dichotomous data sets (106 filters). The detailed results are tabulated in Appendix I. As already outlined in Section 3.11, ten source elemental matrices were used in the fitting. These were:

1. RDUST - The road dust source matrix.
2. TRANSP - The chemical fingerprint associated with vehicular exhaust.
3. INCINR - The source matrix from municipal incineration.
4. LIMEST - Crustal limestone.
5. RSDOIL - Residual oil combustion.
6. SECSO4 - Secondary sulphate.
7. BOF - Basic Oxygen Furnace.
8. BLAST - PACS Blast Furnace.
9. BLSTF - Hamilton Blast Furnace
10. COMP - Iron and Steel Composite.

In order to ensure an accurate and proper CMB source apportionment, source elemental matrices specific for the airshed under study should be obtained. A detailed chemical analysis of each major particle source is Hamilton was not available however, and could not be obtained within the scope of this study. Therefore source "fingerprints" obtained from other airshed studies and published information were used to supplement what information was available. The resulting source matrix is suitable on a semi-quantitative basis; however, care must be taken in the interpretation of the results achieved.

Exceptions were the road dust component (RDUST) which was determined from samples obtained during the study, a blast furnace component (BLSTF) and a basic oxygen furnace component (BOF); the latter two were determined from samples of emission control catches analyzed during earlier studies in Hamilton.

An XRF scan of seven bulk (< 400 mesh) road dust samples revealed three potential groupings based on small differences in the Fe/Si, Ni/Si, Cu/Si, Pb/Si, Zn/Si and Cl/Si ratios. After three composite samples were formed, resuspended and size sampled onto dichotomous filters and analyzed, it was determined that the differences were too subtle to distinguish between them with CMB source apportionment and a single weighted-average source matrix was formed for both the fine and coarse fractions (Tables 4-25 and 4-26).

Composite Sample 1 was formed from samples collected at the Control site on July 5, July 18 and August 8, 1979. These samples had the lowest Fe/Si, Ni/Si and Cu/Si ratios. Composite Sample 2 was made up of material from one sample only (Control site, August 27, 1979). This sample had intermediate Fe/Si, Ni/Se and Cu/Si ratios and the highest Zn/Si value. Composite Sample 3 was composed of samples collected at the Experimental site (July 4, July 17 and August 20, 1979). These samples had the highest Fe/Si, Ni/Si, Cu/Si, Pb/Si and Cl/Si values. Element to silicon ratios were used to examine the preliminary data due to the abundance of silicon in geological material, thus permitting excess elemental concentrations of possible anthropogenic origin to be examined. As noted, only small (but systematic differences between the road dust samples could be detected and therefore, a single Hamilton road dust source matrix was formed for each of the two size fractio

Of the ten particle sources used, typically only four to six were required to fit the observed receptor filter elemental matrix as determined by XRF analysis. Typical CMB results are presented in Tables 4-27 and 4-28.

The sources fit along with their predicted contribution to the total measured ambient mass concentration in $\mu g/m^3$ and percent is listed for each filter. The total ambient mass concentration is given at the bottom of the printout. Also listed are the chemical species used in the CMB program, their measured concentration in $\mu g/m^3$, the percent their measured concentration is of the total ambient concentration, the predicted (or calculated) value determined from the CMB program

TABLE 4-25

Hamilton Road Dust - Elemental Composition

(Fine Fraction)

	PERCENT COMPOSITION (Uncertainty in Parenthesis)			
ELEMENT	COMPOSITE Sample 1	COMPOSITE Sample 2	COMPOSITE Sample 3	SOURCE MATRIX FORMED
Fe	4.1 (.2)	6.5 (.4)	5.9 (.3)	4.9 (.2)
Ni	.03 (.01)	.017 (.010)	.024 (.009)	.023 (.009)
Cu	.04 (.01)	.06 (.02)	.09 (.01)	.056 (.014)
Zn	.28 (.03)	.50 (.04)	.30 (.03)	.34 (.03)
Br	.02 (.01)	.02 (.01)	< .009	—
Pb	.36 (.05)	.49 (.06)	.36 (.04)	.39 (.04)
Rb	< .02	< .02	< .01	—
Sr	.03 (.01)	.04 (.02)	.03 (.01)	—
Ag	.09 (.06)	.08 (.07)	.10 (.05)	—
Sn	.21 (.18)	.20 (.19)	< .1	.20 (.18)
Ga	< .01	< .01	< .007	—
Mg	2.6 (.2)	3.3 (.2)	3.5 (.2)	—
Al	6.4 (.4)	7.3 (.4)	5.1 (.3)	6.0 (.3)
Si	16.3 (.8)	20 (1)	14.7 (.8)	16.4 (.8)
P	.45 (.05)	.52 (05)	.81 (.06)	—
S	.7 (.2)	1.1 (.2)	.9 (.1)	.89 (.14)
Cl	.34 (.08)	.25 (.08)	.43 (.07)	.35 (.07)
K	1.2 (.1)	1.4 (.1)	1.07 (.08)	1.2 (.1)
Ca	7.9 (.4)	11.7 (.6)	12.5 (.6)	9.8 (.4)
Ti	.29 (.03)	.29 (.03)	.26 (.03)	.28 (.03)
V	.014 (.011)	.03 (.01)	.018 (.009)	.02 (.01)
Cr	.03 (.01)	.07 (.01)	.032 (.008)	.039 (.008)
Mn	.18 (.02)	.28 (.03)	.25 (.02)	.23 (.02)

TABLE 4-26

Hamilton Road Dust - Elemental Composition (Coarse Fraction)

ELEMENT	PERCENT COMPOSITION (Uncertainty in Parenthesis)			
	COMPOSITE Sample 1	COMPOSITE Sample 2	COMPOSITE Sample 3	SOURCE MATRIX FORMED
Fe	4.3 (.2)	6.5 (.3)	5.9 (.3)	5.2 (.2)
Ni	.010 (.002)	.013 (.003)	.014 (.002)	.012 (.002)
Cu	.038 (.004)	.045 (.006)	.060 (.005)	.046 (.004)
Zn	.23 (.01)	.35 (.02)	.24 (.01)	.25 (.01)
Br	.016 (.002)	.010 (.003)	.022 (.003)	--
Pb	.28 (.02)	.30 (.02)	.33 (.02)	.30 (.02)
Rb	.009 (.003)	.009 (.004)	.004 (.002)	--
Sr	.039 (.004)	.039 (.005)	.028 (.003)	--
Ag	.02 (.01)	.04 (.02)	.03 (.01)	--
Sn	< .02	< .04	< .04	0
Ga	< .002	< .006	< .002	--
Mg	1.8 (.1)	2.3 (.1)	2.2 (.1)	--
Al	4.3 (.2)	5.5 (.3)	3.9 (.2)	4.4 (.2)
Si	15.2 (.8)	18.3 (.9)	13.4 (.7)	15.3 (.7)
P	.27 (.02)	.32 (.03)	.46 (.03)	--
S	.74 (.06)	1.00 (.09)	.89 (.07)	.85 (.06)
Cl	.34 (.03)	.35 (.04)	.36 (.03)	.35 (.03)
K	1.29 (.07)	1.31 (.08)	1.08 (.06)	1.20 (.06)
Ca	10.0 (.5)	12.6 (.6)	12.5 (.6)	11.5 (.5)
Ti	.36 (.02)	.39 (.02)	.30 (.02)	.35 (.02)
V	.026 (.004)	.024 (.006)	.021 (.004)	.024 (.004)
Cr	.036 (.003)	.057 (.006)	.042 (.004)	.041 (.004)
Mn	.19 (.01)	.27 (.02)	.23 (.01)	.22 (.01)

[illegible]ypic[illegible] Res[illegible] o[illegible] A[illegible]ysi[illegible]ne [illegible]ctio[illegible]

```
CMBDEQ RESULTS FOR CMB # 010106
 FINE  PARTICULATE FRACTION
 SAMPLING DATE: 790712   SITE: EXPT      SITE CODE: 0000001
SAMPLING DURATION: 12 HRS. WITH START HOUR:  6
BACKGROUND SITE SUBTRACTED: NO
 EFFECTIVE VARIANCE FITTING.  REDUCED CHI SQUARE:   4.239 D OF F:  5
 CODE SOURCE FLG      UG/M3                 %
 ---------------------------------------------------------------------
  1    RDUST   *    1.136+- 0.256     2.750+- 0.649
  2    TRANS   *    3.864+- 0.568     9.357+- 1.525
 13    SECSO   *   20.633+- 1.824    49.959+- 5.640
 22    COMP    *    1.472+- 0.205     3.563+- 0.555
 ---------------------------------------------------------------------
       TOTAL:      27.105+- 1.938    65.630+- 6.578
 SPECIE                 FINE  SUSPENDED PARTICULATE
 CODE             MEAS. UG/M3   PERCENT  CALC. UG/M3          RATIO
 ---------------------------------------------------------------------
   1 AL               <  0.033     ---      0.092+- 0.014  0.000+-0.000  AL
   2 SI *     0.250+- 0.031    0.606      0.216+- 0.035  0.863+-0.185  SI
   3 S  *     5.184+- 0.334   12.553      5.184+- 0.282  1.000+-0.077  S
   4 CL               <  0.006     ---      0.145+- 0.032  0.000+-0.000  CL
   5 K        0.159+- 0.010    0.385      0.033+- 0.004  0.206+-0.029  K
   6 CA *     0.135+- 0.008    0.327      0.233+- 0.066  1.723+-0.979  CA
   7 TI       0.010+- 0.006    0.023      0.017+- 0.014  1.773+-3.033  TI
   8 V        0.012+- 0.004    0.030      0.000+- 0.000  0.034+-0.020  V
   9 CR               <  0.003     ---      0.005+- 0.001  9.999+-9.999  CR
  10 MN *     0.047+- 0.004    0.113      0.035+- 0.007  0.752+-0.174  MN
  11 FE *     0.277+- 0.016    0.670      0.365+- 0.084  1.319+-0.504  FE
  12 NI *             <  0.001     ---      0.005+- 0.001  0.000+-0.000  NI
  13 CU       0.023+- 0.002    0.056      0.006+- 0.001  0.265+-0.051  CU
  14 ZN *     0.110+- 0.007    0.267      0.084+- 0.016  0.762+-0.179  ZN
  15 SN               <  0.003     ---      0.002+- 0.002  0.000+-0.000  SN
  16 SB               <  0.002     ---      0.000+- 0.000  0.000+-0.000  SB
  17 BR *     0.091+- 0.005    0.222      0.206+- 0.070  2.251+-1.883  BR
  18 PB *     0.623+- 0.035    1.509      0.538+- 0.080  0.863+-0.170  PB
  19 SO4              <  0.001     ---     15.062+- 0.743  0.000+-0.000  SO4
  20 NO3              <  0.001     ---      0.000+- 0.000  0.000+-0.000  NO3
  21 VC               <  0.001     ---      1.666+- 0.333  0.000+-0.000  VC
  22 NC               <  0.001     ---      1.009+- 0.373  0.000+-0.000  NC
 ---------------------------------------------------------------------
MEAS. AMB. MASS (UG/M3):  FINE:  41.3   COARSE:  32.2   INHAL:  73.5
  * - FITTING ELEMENT
```

TABLE 4-28

Typical Results of CMB Analysis-Coarse Fraction

```
CMBDEQ RESULTS FOR CMB # 010106
COARSE PARTICULATE FRACTION
 SAMPLING DATE: 790712   SITE: EXPT    SITE CODE: 0000001
SAMPLING DURATION: 12 HRS. WITH START HOUR:  6
BACKGROUND SITE SUBTRACTED: NO
 EFFECTIVE VARIANCE FITTING.  REDUCED CHI SQUARE:   1.093 D OF F: 11
 CODE SOURCE FLG      UG/M3              %
-----------------------------------------------------------------------------
  1   RDUST   *  20.858+- 1.558   64.777+- 7.580
  2   TRANS   *   1.134+- 0.206    3.521+- 0.713
 13   SECSO       0.000+- 0.000    0.000+- 0.000
 22   COMP    *   0.419+- 0.240    1.301+- 0.755
-----------------------------------------------------------------------------
      TOTAL:     22.411+- 1.590   69.600+- 7.980
 SPECIE
 CODE                  COARSE SUSPENDED PARTICULATE
              MEAS. UG/M3    PERCENT  CALC. UG/M3          RATIO
-----------------------------------------------------------------------------
   1 AL  *   0.624+- 0.088    1.938    0.964+- 0.167  1.544+-0.492  AL
   2 SI  *   2.750+- 0.438    8.540    3.257+- 0.521  1.184+-0.294  SI
   3 S   *   0.627+- 0.367    1.946    0.243+- 0.049  0.388+-0.084  S
   4 CL  *   0.085+- 0.021    0.265    0.106+- 0.011  1 248+-0.204  CL
   5 K   *   0.258+- 0.027    0.803    0.256+- 0.021  0.989+-0.114  K
   6 CA  *   2.996+- 0.181    9.303    2.466+- 0.313  0.823+-0.135  CA
   7 TI  *   0.089+- 0.012    0.276    0.073+- 0.010  0.827+-0.152  TI
   8 V             <  0.005    ---     0.005+- 0.001  0.000+-0.000  V
   9 CR  *   0.010+- 0.003    0.031    0.010+- 0.002  0.979+-0.291  CR
  10 MN  *   0.049+- 0.005    0.153    0.057+- 0.009  0.979+-0.291  MN
  11 FE  *   1.322+- 0.083    4.106    1.247+- 0.230  0.943+-0.239  FE
  12 NI  *   0.006+- 0.001    0.019    0.004+- 0.001  0.600+-0.126  NI
  13 CU      0.026+- 0.003    0.081    0.012+- 0.002  0.461+-0.089  CU
  14 ZN  *   0.079+- 0.006    0.246    0.081+- 0.014  1.028+-0.247  ZN
  15 SN            <  0.003    ---     0.000+- 0.000  0.000+-0.000  SN
  16 SB            <  0.003    ---     0.000+- 0.000  0.000+-0.116  SB
  17 BR  *   0.044+- 0.004    0.137    0.045+- 0.014  1.018+-0.459  BR
  18 PB  *   0.175+- 0.015    0.543    0.171+- 0.017  0.980+-0.135  PB
  19 SO4           <  0.001    ---     0.000+- 0.000  0.000+-0.000  SO4
  20 NO3           <  0.001    ---     0.000+- 0.000  0.000+-0.000  NO3
  21 VC            <  0.001    ---     0.436+- 0.087  0.000+-0.000  VC
  22 NC            <  0.001    ---     0.464+- 0.172  0.000+-0.000  NC
-----------------------------------------------------------------------------
   MEA   AN   MAS  UG   :   NE   1.    CO   SE:    2.2   IN   :   5
```

and the ratio of the calculated value to the measured value.

The chemical species used as fitting elements are marked with an asterisk. A predicted concentration for the other (nonfitting) chemical species can be calculated with the CMB program but they are not involved statistically in determining the best fit. Chemical species for which there is missing data have "less than" or very low concentration values or which are often associated with sampling artifacts (e.g., Cu) are generally not used as fitting elements. For example, in this study chromium was only used for a fitting element with a portion of the filters when its concentration was substantially above the uncertainty level. When a low concentration or a "less than" value was encountered, chromium was removed from the list of fitting elements. Since a full data set was not available for SO_4^{2-}, NO_3^-, VC (volatilizable or organic carbon) or NVC (nonvolatilizable or elemental carbon), they were not included as fitting elements but a predicted value was determined for them. The elements Co, Ga, Ge, As, Se, Rb, Sr, Cd, W and Hg were not used in the CMB program because of their low ambient concentrations. The elements P and Ba were not used because of the combination of their relatively low concentration and the fact that many of the source matrices used did not have a chemical fingerprint for them.

The quality of a CMB fit is determined by three factors:

1. The reduced chi square
2. The ratio of the calculated to measured values for each major chemical species, and
3. The percent of the total measured ambient concentration which is explained.

Each of these parameters are included on the computer printout for each filter. The closer the reduced chi square is to zero and the closer the calculated to measured ratios are to one, the better is the CMB fit. Moreover, the greater the fraction of the total ambient concentration which is explained the better is the CMB fit. However, 20 to 40 percent unexplained mass is common due to elements which are not included in source or ambient analyses, viz., N, O, H, C. Summary data are presented in Table 4-29 and 4-30. It should be emphasized that the sources fit in a CMB program are not a unique set of sources but rather those which best meet the three previously mentioned criteria.

TABLE 4-29

SOURCE CONTRIBUTIONS AT EXPERIMENTAL SITE

COARSE FILTERS:

Total Number of Filters = 29
Average Reduced Chi Square = 2.65
Average Percent of Mass Explained = 71.4 %
Average Coarse Ambient Concentration = 26.4 μg/m^3

Composite Sources	Average Contribution on Filters to Which Source Was Fit	Number of Filters To Which Source Was Fit
Road Dust	51.4 %	29
Transportation	4.4 %	29
Limestone	6.2 %	15
Sulfate	2.9 %	8
Steel/Iron Sources	6.7 %	19

FINE FILTERS:

Total Number of Filters = 29
Average Reduced Chi Square = 2.66
Average Percent of Mass Explained = 78.4
Average Fine Ambient Concentration = 28.1 μg/m^3

Composite Sources	Average Contribution on Filters to Which Source Was Fit	Number of Filters To Which Source Was Fit
Road Dust	2.0 %	23
Transportation	16.6 %	29
Sulfate	55.6 %	29
Incineration	0.6 %	7
Steel/Iron Sources	6.6 %	29
Residual Oil	0.04%	3

TABLE 4-30

SOURCE CONTRIBUTIONS AT CONTROL SITE

COARSE FILTERS:

Total Number of Filters = 24
Average Reduced Chi Square = 2.45
Average Percent of Mass Explained = 71.7
Average Coarse Ambient Concentration = 29.1 $\mu g/m^3$

Composite Sources	Average Contribution On Filters To Which Source Was Fit	Number of Filters To Which Source Was Fit
Road Dust	44.3 %	24
Transportation	5.3 %	24
Limestone	3.9 %	11
Sulfate	12.2 %	12
Steel/Iron Sources	7.7 %	17

FINE FILTERS:

Total Number of Filters = 24
Average Reduced Chi Square = 2.81
Average Percent of Mass Explained = 71.3 %
Average Fine Ambient Concentration = 26.1 $\mu g/m^3$

Composite Sources	Average Contribution On Filters To Which Source Was Fit	Number of Filters To Which Source Was Fit
Road Dust	1.4 %	16
Transportation	13.8 %	24
Sulfate	46.4 %	24
Incineration	0.8 %	7
Steel/Iron Sources	7.6 %	24

Coarse Fraction Apportionment. The CMB apportionment for the coarse particulate fraction identified four principal particle sources: (1) road dust, (2) transportation, (3) limestone and (4) the steel/iron industry. On two filters, excess sulphur (probably sulphate) was also detected. The CMB fits are very good with reduced chi square values averaging between 2 and 3 with most elemental ratios near unity and between 70 and 80% of the mass typically explained. The quality of the fit is due to the fact that the road dust component is the major contributor in the coarse fraction (40 - 50%) and it has been chemically well characterized. These values of chi square are statistically significant at about 90% confidence level (variable from case to case because of the differing number of degrees of freedom, which equals the number of elements fit minus the number of components fit).

Vehicular exhaust had a small contribution in the coarse fraction which is usual in an urban environment. The steel/iron component was approximated by the use of four source fingerprints: (1) an iron and steel intergrated complex composite, (2) a blast furnace (Portland), (3) another blast furnace (Hamilton, and (4) a basic oxygen furnace (Hamilton). These sources were combined in obtaining an average estimate for the steel/iron industry's contribution as it is unlikely that the individual fingerprints are actually indicative of the specific source which is implied by the name but rather are the best fit for the enrichment in metal (viz., Fe, Mn, Cu, Zn) found in the ambient particle data. There is no significant difference observable between the Control and Experimental sites. It should be emphasized that while the mean values listed in Tables 4-29 and 4-30 are useful in understanding the relative importance of pollution sources, there was considerable variability from filter to filter. Also, variability in meteorologic conditions and emission levels is clearly of significance, and is discussed later.

Fine Fraction Apportionment. The CMB source apportionment for the fine fraction was also a very good fit (an average reduced chi square of 2 to 3, as for the coarse fraction). The single principal source in the fine fraction is sulphate. This source was determined as follows: after the contributions to sulphur from al sources were combined, excess unexplained sulphur was always present on each filter The pure secondary ammonium sulphate fingerprint was then used in each case to account for the remaining sulphur. Similarly in nearly every case there was much less chlorine and much more potassium in the Hamilton particulate data than was explained by the standard source fingerprints which were used. Not surprisingly, a significant vehicular exhaust contribution (transportation) was detected in the fine fraction. A small road dust component was also noted in most filters and a very small residual oil contribuiton was seen in three filters (high V). Data from other airsheds show that typically about 90% of the road dust mass is in the coarse fraction and about 10% of the mass in in the fine fraction (239). This compares favourably with the average road dust data of the Experimental and Control sites which had 2.1% and 1.5% of the total road dust mass in the fine fraciton, respectively.

To explain the metal content (Fe, Ni, Cr, Mn, Pb, Cu, Zn and Sn), the same four steel/iron sources as used with the coarse fraction were used and the same caveat applies to their interpretation. Additionally, a municipal incineration source was used to explain Zn, Sn and a portion of the Pb concentration. Because municipal incineration emissions have very high chlorine concentrations due to plastics such as PVC, chlorine was always over-predicted when this component was fit. Industrial incineration may not have such large concentrations of chlorine associated with it. Alternatively, the Zn, Sn and Pb (over that which is due to vehicular exhaust) may be partially due to some other undefined process.

During the mechanical and vacuum sweeping periods, CMB data indicate that road dust contributed an average of about 15 $\mu g/m^3$ and 11 $\mu g/m^3$, respectively. Data were not available for the baseline period due to equipment problems. A comparison between the Experimental and Control sites shows no statistically significant differences between total inhalable (< 15 μm) particulate matter loadings at the sites during these street cleaning periods. This is discussed more fully in Section 5.2 and 5.3.

4.8 Disperison Modelling Results

4.8.1 Modelling Procedures

The modified PAL model described in Section 3.10 was used to simulate particulate dispersion from local traffic and area sources around the Experimental and Control sites was well as the major point sources in Hamilton. In order to provide a statistically significant data sample, the complete time series was simulated on an hourly basis using hourly meteorological data.

Table 4-31 documents the application of the model in terms of simulation

TABLE 4-31

Basis for Model Applications

Model Application	Period	Receptor Sites	Meteorological Data	Emissions Data
Series 1 Full Period Simulative	June 10 Sept. 06	E1-E4,E6	Woodward Tower for stability & winds Level 2 for P & A sources Level 1 for L sources	Local streets & Areas with varying emissions according to traffic volume
Series 2 Comparison Period for Control site	July 1-31	E1-E4,E6 C1-C3	"	Area Emissions constant over period
Series 3 Met Data Test	July 1-31	E1-E4,E6	Tower for P & A sources Control site winds for line sources	"
Series 4 Emissions Data Test	July 1-31	E1-E4,E6	Tower for P,A & L sources	Doubled Resolution on Area Sources

period and input data characteristics. The Series 1 runs represent the primary output of the modelling program and form the basis for comparison with measured TSP values. The Series 2 runs provide a comparison between the Experimental and Control site predicitons, and are discussed in Section 5. The Series 3 runs for the month of July were performed as a test of the applicability of lower tower wind data for modelling experimental site roadway emissions. It was found that the use of experimentalsite winds would provide a much reduced data set due to the large number of missing observations. The use of control site winds showed little difference for roadway contribution, particularly for longer-term averaging. It was, therefore, decided to use the Tower winds for Series 1 runs because of their completeness. The Series 4 runs were designed to test the effect of resolution of area source emissions. In these runs, the resolution was doubled, producing 4 times as many areas, and the inventory was recalculated on the smaller areas. It was found that the higher resolution inventory produced very little change (maximum difference of the order of several percent) in 6-hourly averaged TSP at the Experimental Site. Due to the large savings in computer time, the Series 1 runs use the coarser resolution emission inventory.

In all runs, hourly concentrations of particulates were calculated and stored separately on file. The several contributions, point, area and line (roadway), were kept distinct, as was the complete sequence for each receptor site. Longer-term averages, corresponding to the 6-hourly sampling frequency were then computed as the arithmetic mean of the six 1-hourly values for the corresponding period.

4.8.2 Long-term Concentration Averages

The model predictions of the long-term averages corresponding to the 3 experimental periods are presented in Table 4-32. The point, area and line components are shown, as is the mean background influx for the month. The latter is obtained from measured TSP at the School, Farm, or SRC site for each 6-hourly period (or 12-hourly period) available, where the minimum of the 3 values was selected as most representative of general background influx.

Also shown in Table 4-32 is the mean of the measured TSP values and the ratio of total predicted to measured TSP. For the Baseline Period, the predicted TSP averages are within 15% of the observed values at the experimental monitors, showing good agreement in magnitude, as well as the drop-off with height and off-

TABLE 4-32

Arithmetic Mean Predictions of Suspended Particulates ($\mu g/m^3$) at Experimental Site

		Exp 1	Exp 2	Exp 3	Exp 4	Exp 5
	P	8	8	8	9	9
	A	34	47	49	49	47
Period 1	L	3	7	13	6	4
June 10-July 6	B	42	42	42	42	42
(Baseline)	T	87	103	112	104	100
	Obs	92	99	109	92	87
	Pred/Obs	0.95	1.04	1.03	1.13	1.15
	P	8	8	8	8	8
	A	49	68	72	65	63
	L	4	10	17	9	7
Period 2	B	56	56	56	56	56
July 7-Aug. 7	T	117	142	152	139	134
(Mechanical	Obs	93	100	119	99	98
Sweeping)	Pred/Obs	1.26	1.42	1.28	1.40	1.37
	P	8	8	8	8	9
	A	40	58	61	56	53
	L	4	9	15	7	6
Period 3	B	39	39	39	39	39
Aug. 8-Sept. 8	T	91	113	123	110	106
(Vacuum	Obs	83	90	101	83	83
Sweeping)	Pred/Obs	1.10	1.26	1.22	1.33	1.28

KEY

P = Point Source Contributions
A = Area Source Contributions
L = Line Source Contributions
B = Background Contributions
T = Total Predicted Loading

road distance.

The predictions show an average contribution of approximately 8 $\mu g/m^3$ from the point sources, corresponding to 8% of the low-level TSP. The local roadway contribution is of the order of 13% at the 4 m level, dropping to 3% of the 15 m level. The area source contribution (of which 50% to 80% are traffic related) contribute approximately 40% of TSP, with a similar contribuiton from the background.

During the second period, a significant increase in TSP is predicted over the first period. About half of the increase is related to ghe significant increase in background level, and is likely an overprediction of background for the period. If this effect is taken into account, an 18% increase is predicted over the June period. The observed data show a 9% increase for the period. It is seen that the bulk of the increase is related to the large increase in area contribution, the latter resulting from a higher frequency of low wind speed and south to southeasterly flows.

The roadway contribution is likewise higher in the second period, although the 30% increase is not significant in absolute terms.

Period 3 predictions indicate an incrase of 10% over period 1, whereas the data show a 9% decrease. Again, the predicted increase is related to an increase in the area contribution.

The diurnal variation in TSP predictions for the Experimental 3 site is shown in Table 4-33. In this Table, Local refers to the total predicted TSP from point, area and line sources, as opposed to the background influx. Both components show a diurnal pattern.

The TSP predictions show a peak in the afternoon period for June, whereas the other two periods show a peak in the morning, remaining nearly constant in the afternoon and evening periods.

Table 4-34 shows the directional contribution to the TSP from Local sources at Experimental 3 site, indicating that 60 to 65% of the loading is related to influx from the SE to S sectors. A more complete breakdown of TSP contributions by Period, time of day, wind direction and wind speed is tabulated in Appendix J.

The vertical profile to TSP at the Experimental Site is shown in Figure 4-11, and compared to the measured profile. The measured profiles show a rapid decrease between the 4 m and 8 m levels, and a much smaller decrease above the 8 m

TABLE 4- 33

Diurnal Variation of TSP at Experimental 3 ($\mu g/m^3$) Arithmetic Average

		00-06 LST	06-12 LST	12-18 LST	18-24 LST
P1	Local	36	74	83	94
	Background	37	41	54	36
	Total	73	115	137	130
P2	Local	80	113	83	117
	Background	50	61	65	49
	Total	130	174	148	166
P3	Local	68	102	88	101
	Background	36	43	41	37
	Total	104	145	129	138

P1 = Baseline Period

P2 = Mechanical Sweeping

P3 = Vacuum Sweeping

TABLE 4-34

Directional Contribution to TSP at Experimental 3 Site from Local Sources

	Directional Sectors (degrees, due North)*			
Period	346-075	076-165	166-255	256-345
P1	71	111	59	46
P2	78	148	93	73
P3	69	151	83	57
Avg.	73	137	78	59

P1 = Baseline Period

P2 = Mechanical Sweeping

P3 = Vacuum Sweeping

* For comparison, the directional sectors used to classify meteorological regimes in earlier sections (Figures 3-27) were as follows:

$$r_1 = 112.5^\circ - 292.5^\circ$$

$$r_2 = 22.5^\circ - 112.4^\circ$$

$$r_3 = 292.6^\circ - 22.4^\circ$$

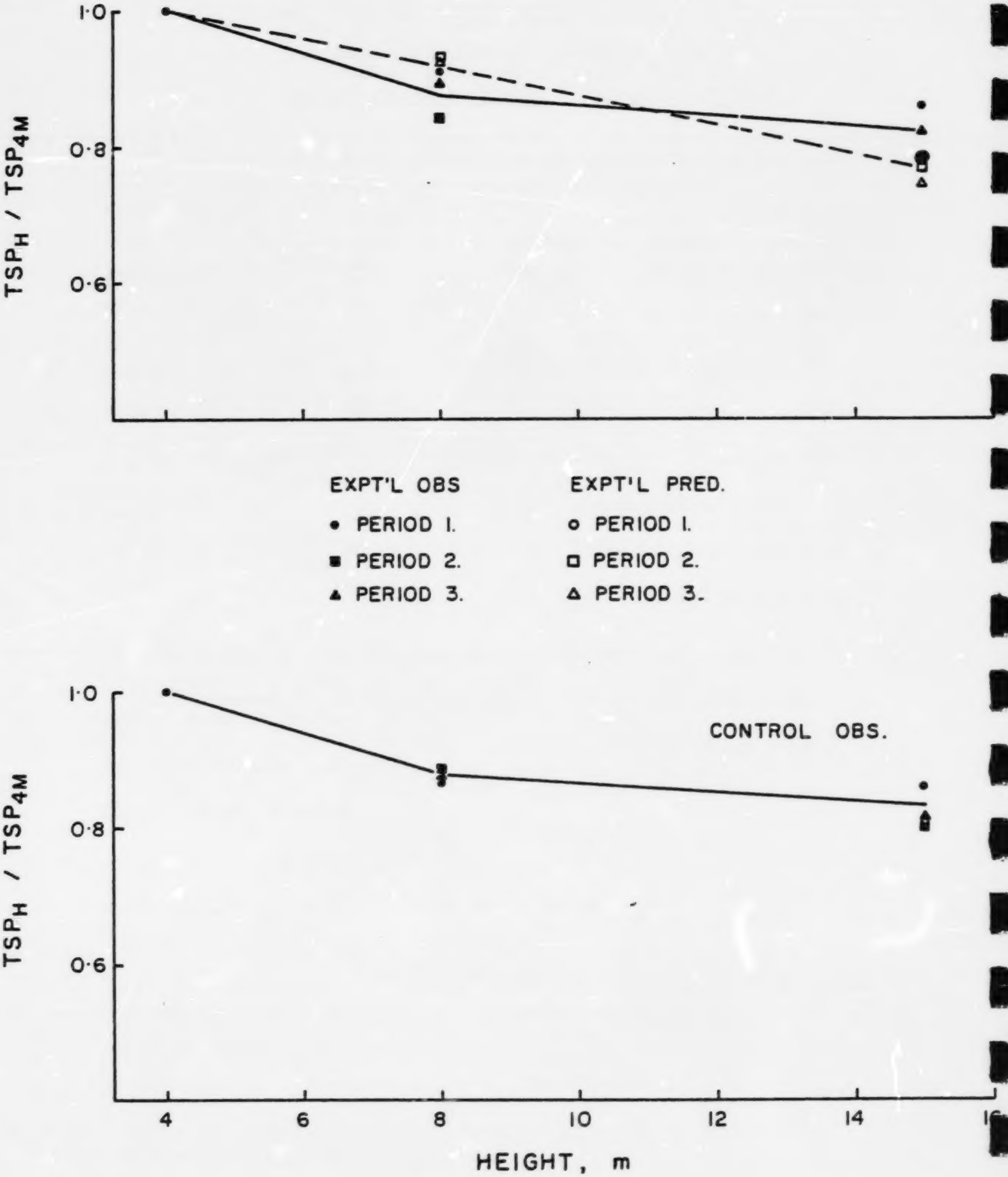


FIGURE 4-11 HEIGHT PROFILE FOR PREDICTED TSP

level, with a 20% total decrease in TSP.

The predicted TSP drops off less rapidly at first, but continues to decrease at about the same rate for a total decrease of 25%. These results would seem to indicate that the assumed area source height for the model runs was too low.

For comparison purposes, a parallel period of runs for the Experimental and Control sites was carried out. Table 4-35 shows the predicted and actual TSP for the two sites for the period July 1 to July 31. For this period, the Control site predictions are closer to actual than are the Experimental site predictions.

4.8.3 Short-term Concentrations

The 6-hourly average TSP were evaluated against measurements to test the faithfulness of the modelling precedures and the meteorological data.

Figure 4-12 shows the sequence of actual and predicted TSP for the periods 73 - 105 at Experimental sites 1 to 3. The separate contributions in the predicted values are shown in each box in the order Point (lowest rectangle, when non-zero), Area (shaded), Line and Background (top, always non-zero).

The full time series of predictions for the Experimental Sites are tabulated in Appendix J. Table 4-36 lists the prediction statistics for the three periods for the Experimental Sites. In addition to the arithmetic means and standard deviations of predicted and actual TSP, also listed is the correlation coefficient for 6-hourly TSP at a given site with the corresponding 6-hourly observations. The coefficient range from 0.4 to 0.6 on the basis of the entire period, indicating that the model predicts TSP levels reasonably well.

The standard deviation listed in Table 4-36 is calculated from the average of the absolute logarithm of the ratio of predicted to observed 6-hourly concentrations. A mean ratio of 0.18 corresponds to a factor of 1.5, or a 50% error in prediction for a given 6-hourly average.

Table 4-35

Arithmetic Mean Predictions ($\mu g/m^3$) at the Experimental and Control Sites for July 1-31

		Receptor		
		1	2	3
Experimental	P	9	9	10
	A	53	75	79
	L	4	10	16
	B	54	54	54
	T	120	149	158
	Actual	92	100	116
Control	P	8	9	9
	A	40	56	58
	L	8	16	22
	B	54	54	54
	T	110	135	143
	Actual	94	107	119

P = point source contribution
A = area source contribution
L = line source contribution
B = background
T = total

TABLE 4-36

Prediction Statistics: Means, Standard Deviations and Correlation Coefficients for the Three Study Periods

Receptor	No. of Obs.	Means Pred	Means Act	Std Dev Pred	Std Dev Act	Corr Coef	Std. Error	No. of Missing Obs.
PERIOD 1 - Baseline (1-105)								
1	84	86.5	89.6	40.6	52.7	0.5687	0.1397	18
2	93	103.0	96.5	48.6	57.4	0.3782	0.1784	9
3	93	111.0	107.5	50.9	56.9	0.4330	0.1626	9
4	75	104.0	91.9	48.5	55.4	0.5133	0.1673	27
5	80	100.4	86.7	45.6	50.2	0.5125	0.1688	22
PERIOD 2 - Mechanical Sweeping (106-233)								
1	119	116.5	92.8	47.4	47.1	0.5639	0.1647	7
2	124	141.8	100.3	57.4	48.2	0.4797	0.1970	2
3	123	151.8	118.9	60.3	57.3	0.4153	0.1823	3
4	120	139.4	98.6	54.6	49.5	0.4640	0.1988	6
5	122	133.5	98.4	52.3	48.5	0.4982	0.1800	4
PERIOD 3 - Vacuum Sweeping (234-351)								
1	106	90.5	82.7	45.0	43.8	0.4424	0.1540	12
2	112	113.0	89.8	58.4	45.6	0.3809	0.1913	6
3	113	123.0	101.2	62.2	51.5	0.3704	0.1897	5
4	116	110.3	82.6	53.2	42.5	0.4067	0.1935	2
5	114	106.2	83.4	48.7	46.3	0.4141	0.1900	4

Meteorology, all periods: Points & Areas - Upper Level; Lines, lower level.

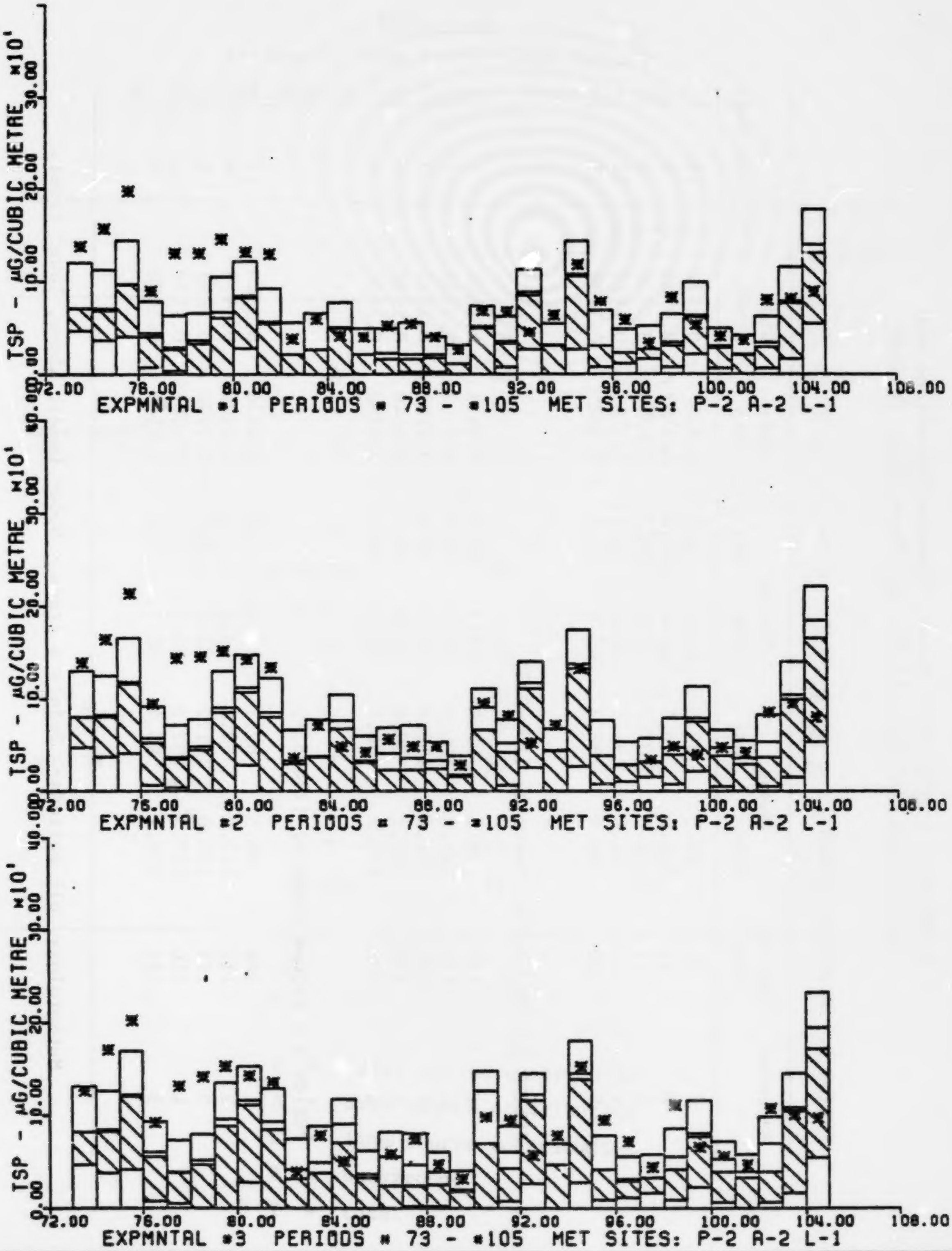


FIGURE 4-12 Dispersion Modelling Results, Height Profile at the Experimental Site

5. DISCUSSION OF RESULTS

The results obtained from the various components of the study have been presented in the previous section in a summarized form with brief comments on the more apparent features of the data. In this section, the results are discussed in the context of the specific objectives of the study. A first and important objective of the study was to characterize in some detail airborne particulate matter in the study area and this topic is dealt with in Section 5.1. A quantitative assessment of the importance of non-traditional sources relative to industrial point source emissions, with special emphasis on reentrained road dust, was another important goal of the study. The preparation of a micro-inventory of sources surrounding the study area, chemical mass balance determinations, and dispersion modelling were the principal techniques used to quantify the contribution of various source categories to ambient TSP levels in downtown Hamilton, and the results are discussed in Section 5.2. As discussed in Section 2.7, most of the earlier studies of the effectiveness of street sweeping as a control method to reduce ambient TSP levels were seriously lacking in experimental design and so a third component of this study was an evaluation of street sweeping methods. The results of this phase of the study are discussed in Section 5.3.

5.1 Characterization of Particulate Matter in the Study Area

5.1.1 Characteristics of the TSP Data

General Features. The TSP values measured at each site were found to follow a log-normal distribution. A typical plot of log TSP versus cumulative frequency shows a straight line, as illustrated for Experimental 3 in Figure 5-1. This distribution is evidence of large scale or general influences rather than a specific predominant source on ambient TSP levels and is generally observed for such data (240).

Because of this log-normal behaviour, the central tendency of the data for a particular site is calculated as a geometric mean, and its variability expressed as a geometric standard deviation (GSD). This means that 67% of the data lie within ± 1 GSD of the natural logarithm of the geometric mean. For example, for Experimental 3, the overall geometric mean was found to be 96 $\mu g/m^3$ with a GSD of 0.535. Thus, 67% of the data for

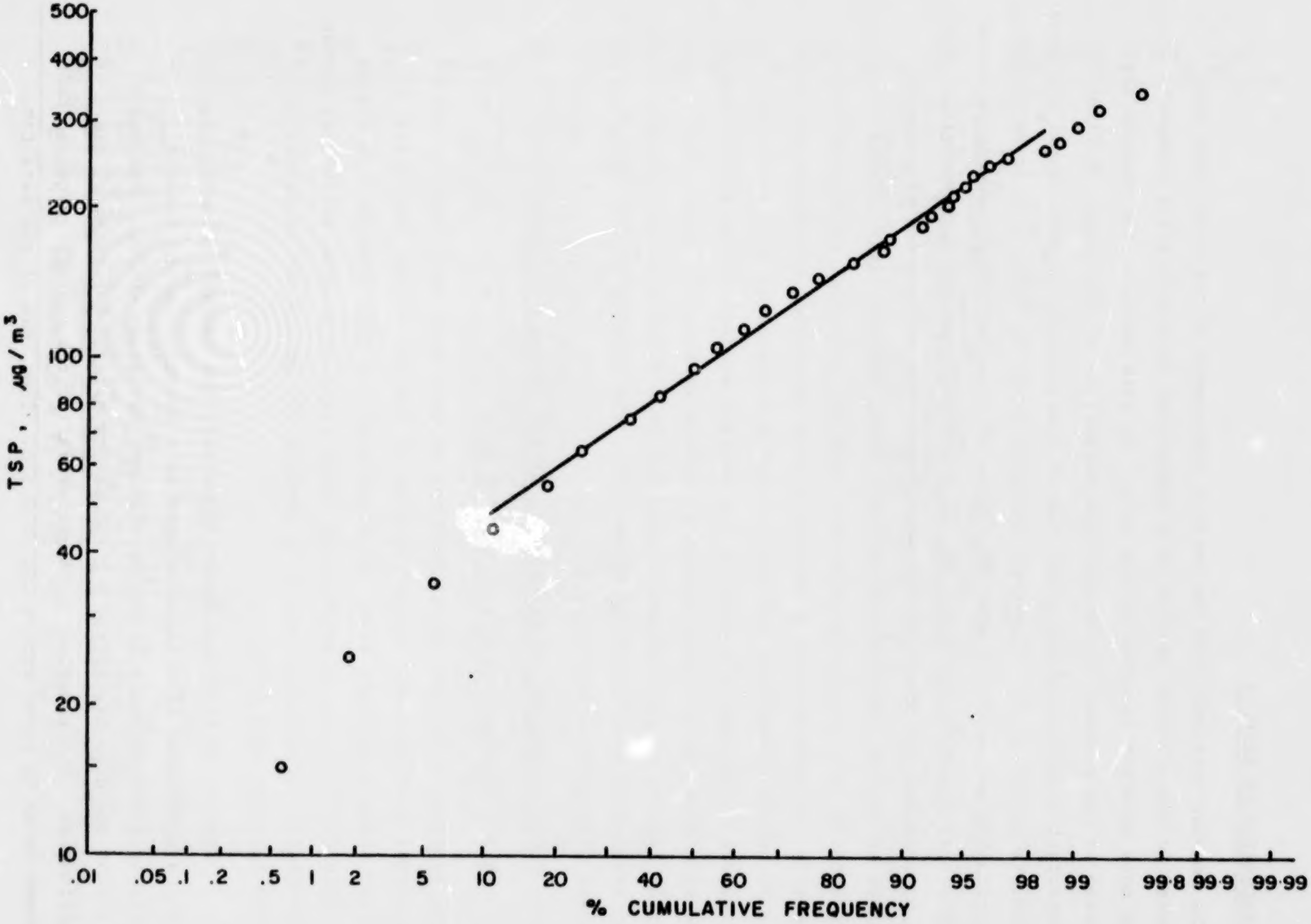


FIGURE 5·1 PLOT OF LOG TSP vs CUMULATIVE FREQUENCY FOR EXPERIMENTAL 3.

Experimental 3 lie within the range of 56-164 μg/m^3 and 99.7% of the data lie within ± 3 GSD of the geometric mean.

As illustrated in Table 4-7, the four sites along Cannon Street have geometric mean TSP values for the overall study, measured at the 4 m level, ranging from 96 μg/m^3 at Experimental 3 to 109 μg/m^3 at John Street. Plus or minus one GSD for these values includes the range 56-186 μg/m^3. These figures can be compared to historical data collected by MOE for downtown Hamilton sites, as illustrated in Table 4-15. The monthly average values for City Hall, Hughson/Hunter and Hughson North range from a low of 35 μg/m^3 to a high of 145 μg/m^3, which compare very well with the results presented above.

The variability of the TSP data at a particular site is illustrated in Figure 4-1, which shows the 6 hourly TSP levels measured at the Experimental 3, Control 3 and SRC sites during the month of July, 1979. The most obvious feature of this illustration is the consistency of the variation of TSP levels from site to site. The observed TSP levels, whether high or low, are similar for both Experimental 3 and Control 3 for the same sample period, and the SRC site shows a similar variability, although at a lower level. This consistency in the TSP variability between Experimental 3 and Control 3 is an indication that the two sites are relatively similar in characteristics, which is necessary for the assessment of the effects of road sweeping discussed in Section 5.3 below.

The variation of TSP at the SRC site reflects the variability of background contributions to TSP. From other studies in the Hamilton area and surrounding rural areas of Southern Ontario (78), the background annual geometric mean TSP has been determined to be approximately 40 μg/m^3, a value which compares well with the mean TSP value for the study period at the SRC site of 45 μg/m^3. The Farm site has an average TSP value for the study period of 56 μg/m^3 which indicates the effects on this site of emissions from the city and industrial area to the northeast.

Effect of Meteorology. Some effects of meteorology can also be observed in Figure 4-1. The effect of precipitation is to lower TSP values by washing particulate matter out of the atmosphere and by wetting dust on roads and other surfaces, thus suppressing reentrainment. This effect is illustrated by the drop in TSP levels indicated at point A in Figure 4-1. During this period of approximately 24 hours, 8.2 mm of rainfall were recorded. The corresponding drop in TSP can be seen for all three sites illustrated, from 150 $\mu g/m^3$ to about 40 $\mu g/m^3$ at Control 3 (a dramatic illustration of this effect) and from 80 $\mu g/m^3$ to 40 $\mu g/m^3$ at the SRC site. Other such events can be observed in the data, on a smaller scale. The overall effects of precipitation will be more fully discussed below.

However, large variations in TSP levels can also occur due to shifts in wind direction. The two events illustrated by B and C in Figure 4-1, are due to wind shifts from NE to SW. Other variations due to wind shifts can be observed in the data.

Another feature which can be observed in Figures 4-1 to 4-5 is the diurnal variation of TSP. This variation is explained at least in part, by the normal diurnal variation in wind speed. Highest wind speed usually occurs at mid-day, resulting in increased reentrainment of particulate matter. There may also be a diurnal pattern to emission rates and to variations in general urban activity. However, high TSP loadings on occasion also were associated with calm conditions.

In order to statistically assess the effect of meteorological variables, the data were subdivided according to meteorological regimes as listed in Table 4-8. The parameters chosen to define the regimes are those used as selection criteria for filters for analysis as outlined in Section 3.8.2, and illustrated in Figure 3-24. Table 4-8 also contains the geometric standard deviations and the number of events in each regime.

Examination of Table 4-8 reveals a number of interesting features. The highest mean values of TSP for the Cannon Street sites occur for the $r_2u_1p_2$ and $r_2u_2p_2$ regimes. These regimes involve winds from the northeast at speeds from 0 to 8 and 9 to 18 kph, respectively, during periods of no rainfall ($r_2u_2p_1$ while also high, represents only 2 events of fairly low rainfall) and may often involve lake breeze inversions which result in limited depression in the Hamilton area. These conditions are conducive to transport of pollutants from the industrial SRC sector to central Hamilton. Under these conditions, the School and SRC sites have low TSP levels, whereas the Farm site has elevated levels, indicating the effect of transport of suspended particulate matter from the downtown area to the northeast of this site. It should be noted that, during the experimental segment of the study, no strong thermal inversions occurred in the Hamilton area as evidenced by the lack of any high Ontario Air Pollution Index values during this period. Such conditions can result in even higher levels than observed on occasion during the study.

Wind direction effects can be more readily observed if the regime parameters are averaged over all events (i.e., geometric mean of all r_1, all r_2, etc.), as presented in Table 5-1. It can be seen from these results that wind direction has the largest effect on TSP levels, with northeasterly winds (r_2) resulting in the highest value at the downtown Cannon Street sites. Also, the Farm site has highest TSP values for these conditions. In contrast, when winds are from the ESE to WNW (r_1), the mean TSP value for the School is quite high at 103 $\mu g/m^3$ compared to values of 53 and 47 $\mu g/m^3$ with northeast and northwest winds (r_2 and r_3), respectively. This value of 103 $\mu g/m^3$ reflects the influence of emissions from both the industrial sector located approximately 2 km to the southwest of the School site and the adjacent highway.

Wind speed has a small effect at the Cannon Street sites, with high winds tending to show higher values. Similarly, precipitation has little effect, except at the School site. This is probably because this site is influenced by two specific large sources; the QEW and the industrial sector, rather than by many small area sources and is thus expected to be affected more by precipitation washout and suppression of dust emissions.

The directional distribution of TSP also can be examined in terms of wind roses, average pollutant concentration roses and total pollutant dosage roses. The wind roses for the study period at the MOE Woodward Street tower 10 m and 61 m levels are illustrated in Figure 4-8. The 10 m rose indicates that the prevailing low level winds were out of the southwest, with some distribution to the northeast. The 61 m rose, however, shows prevailing higher level winds from the east, with a significant component from the east-southeasterly direction.

TABLE 5-1

TSP Averages for Each Regime Parameter (g.m. $\mu g/m^3$)

	E1	E2	E3	E4	E6	C1	C2	C3	JS	OA	Sc	F	ST
r_1 av.	72	81	94	80	72	70	77	86	102	90	103	51	46
r_2 av.	100	102	115	95	97	119	124	141	138	143	53	71	48
r_3 av.	75	77	85	72	74	86	92	98	95	94	47	52	36
u_1 av.	80	85	94	79	79	89	94	104	105	103	60	61	44
u_2 av.	78	86	99	82	80	82	87	113	115	106	89	61	49
u_3 av.	84	101	121	93	86	78	88	100	132	111	103	38	42
p_1 av.	83	88	97	82	82	83	92	99	108	101	67	51	49
p_2 av.	79	87	100	82	78	84	90	102	115	108	82	60	46

Regime Definitions (Figure 3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = SW Sector	u_3 = > 18 km/hr	

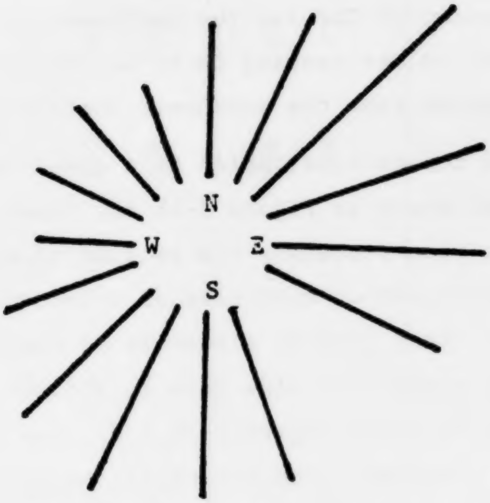
A pollution rose, which presents the average directional distribution of the TSP concentration, is plotted in Figure 5-2a using geometric mean TSP concentrations measured at Experimental 1. This rose shows a fairly even distribution of TSP for the northeast, southeast and southwest quadrants, with highest values tending to be in the northeast quadrant, and significantly lower values from the northwest quadrant.

A normalized dosage rose, which is a combination of a wind and pollution rose, is also shown in Figure 5-2b for Experimental 1. The points of a normalized dosage rose represent the product of wind frequency and geometric mean TSP concentration expressed as a percent of the total dosage for that direction and hence provide a measure of the relative pollutant burden arriving at the monitoring site from this direction. The dosage rose for Experimental 1, as shown in Figure 5-2b, indicates that major sources of TSP matter lie to the northeast (the industrial sector) and to the southwest to south-southwest of the sampler. The SSW direction represents winds blowing directly across the road towards the sampler.

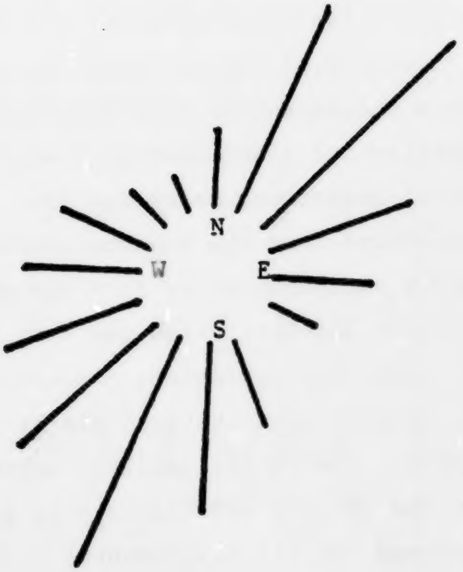
Figure 5-3 shows dosage roses for the Experimental 3, Control 3 at SRC, School and Farm background sites. The roses are arranged to represent the approximate geographical positions of the five sites relative to each other. Beginning in the southwest, the Farm site receives its largest TSP contributions from the NNE and NE, the direction of the downtown Hamilton area. Significant contributions also come from the southwest quadrant, along the path of the prevailing winds. The Experimental 3 and Control 3 sites show contributions from the NE and SW quadrants, reflecting emissions from industry to the NE and road dust and other emissions from the downtown core to the southwest. At the School site, the major contribution is from the southwest, indicating the effects of the nearby heavy industry, with the only other significant contributions coming from a westerly direction, indicating the effects of the QEW. At the SRC site, the largest contributions are from a southwesterly direction, indicating an effect due to the Hamilton urban area, with some specific contribution from the QEW and 403 Highways to the south. The southwesterly contributions observed for the Experimental 3 and Control 3 sites are not apparent using the meteorological regime approach discussed above, because

FIGURE 5-2

Directional Distribution and Normalized Dosage Roses for TSP Concentrations at Experimental 1 Site



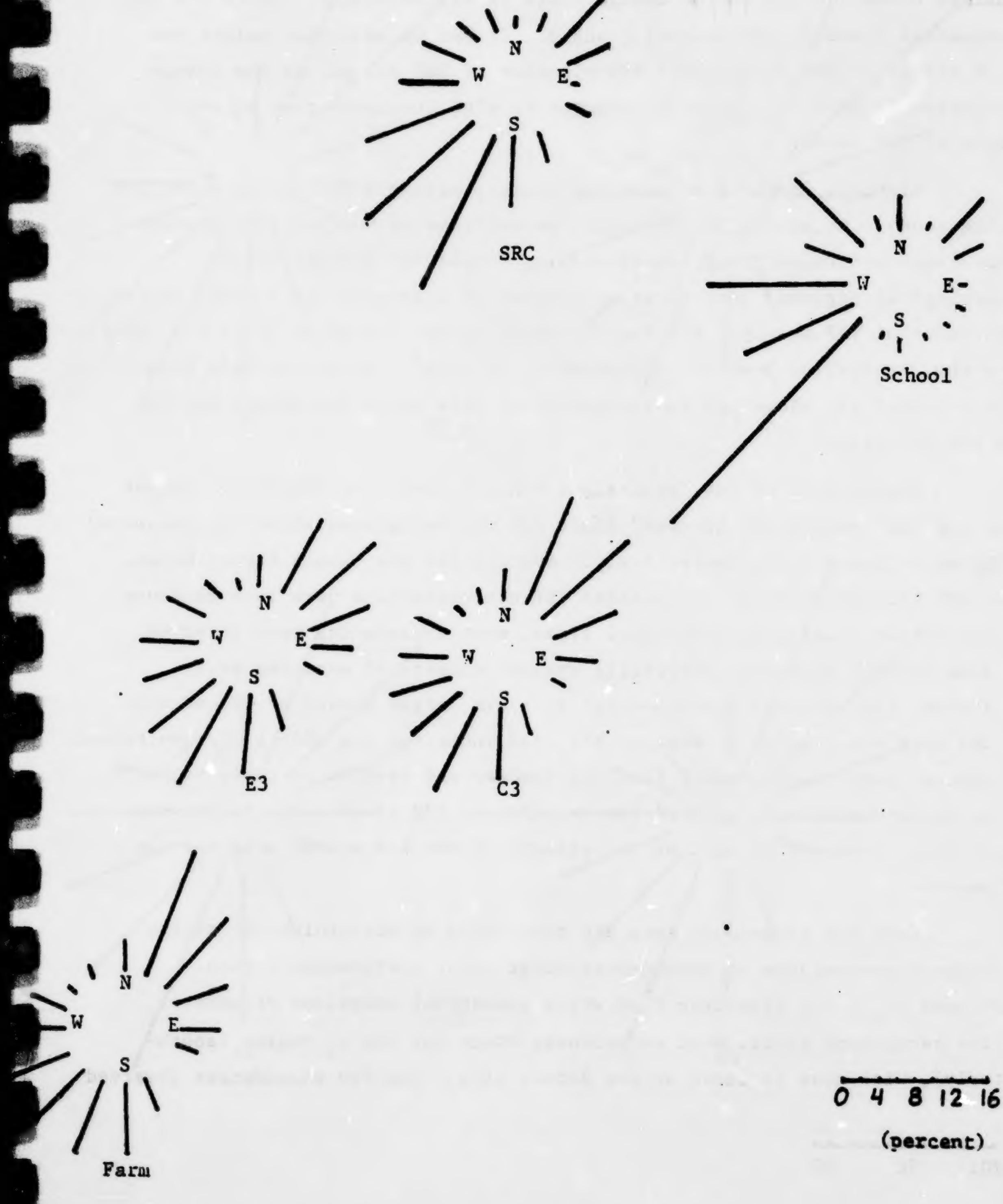
a. Directional Distribution of the Geometric Mean of the TSP Concentration at Experimental 1.



b. Normalized Directional Dosage of TSP at Experimental 1.

FIGURE 5-3

Normalized Directional Dosages of TSP Concentrations at Sampling Sites



the major sector (r_1) includes all winds from ESE to WNW, thus any purely southwesterly contributions are averaged over the larger sector. The effect of height above the roadway on dosage roses is illustrated in Figure 5-4 for Experimental 1 and 3, and Control 1 and 3. It can be seen that height has little effect on the directional distribution of TSP dosage, as the dosage calculation is more influenced by changes in wind frequency than by small changes in TSP level.

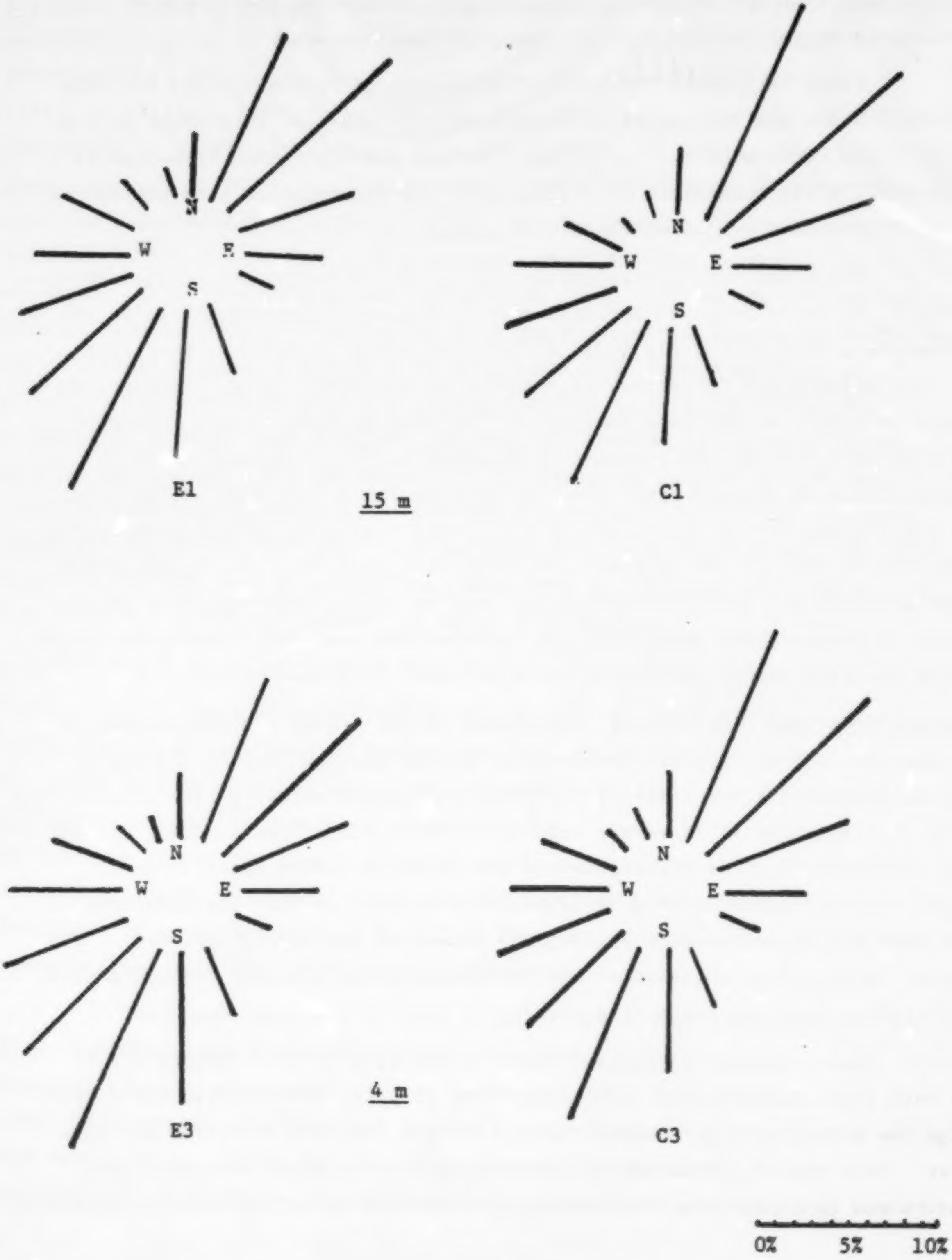
Although comparisons with air quality criteria are not an objective of this study, the equivalent criteria, as outlined in Section 4.2, provide a convenient reference point for discussing trends for the different meteorological regimes. As the study covered an approximately 3 month period, comparisons of TSP averages for the different sites, listed in Table 4-7, would be to the "equivalent 3-month" criterion of 71 $\mu g/m^3$. It can be seen from Table 4-7 that all sites are in exceedence of this criterion except for the Farm and SRC sites.

Exceedences of the "equivalent 6-hour" limit for the Cannon Street sites and the "equivalent 12-hour" limit for the background sites are presented in Tables 4-13 and 4-14, respectively. Overall for the Cannon Street sites, about 20% (590 of 3016) of the sampled TSP concentrations were in exceedence of this 6-hour limit. At individual sites, most exceedences were observed for John Street, with only marginally smaller numbers of exceedences at Oak Avenue, Experimental 3 and Control 3. This larger number of exceedences for the samplers located closest to the road indicates the effect of reentrained and emitted particulate matter from the roadway and traffic on these samplers. At the background sites, most of the exceedences (32 of 39) occurred at the School site, probably because of the effects of the industrial area and the QEW nearby.

When the exceedence data are subdivided by meteorological regime, the highest percentages of exceedences occur under northeasterly wind conditions (r_2), the direction from which industrial emissions originate. For the background sites, most exceedences occur for the r_1 regime (southwesterly), with most of these at the School site. The few exceedences observed

FIGURE 5-4

Normalized Directional Dosages of TSP Concentrations As a Function of Height at Experimental and Control Sites



for the Farm site are in the r_2 regimes, again indicating the effect of particulate matter carried from the downtown Hamilton area.

Table 4-12 lists TSP levels for periods of variable winds and calm periods. Calms are indicative of periods of very stagnant conditions during which little reentraintment can occur. The low average values (compared to the overall study means) are consistent with the fact that no long periods of inversion occurred preceding these calm periods.

The effects of precipitation can be observed from the regime averages p_1 and p_2 in Table 5-1. In general, very little effect of precipitation can be observed, with just a few $\mu g/m^3$ differences being observed at most sites. The only significant difference is observed at the School site. However, as discussed above, at the site located on the Beach Boulevard area, a narrow strip of land forming the entrance to Hamilton Harbour, the lack of any significant area sources other than the QEW and Beach Boulevard implies that the suppression effect of precipitation on road dust would show a more marked reduction in overall TSP levels. However, as discussed above, at the other sites specific precipitation events may lead to significant reduction in TSP levels, although these reductions are averaged out over the longer time period of the study.

Diurnal Variations. The diurnal variations in TSP levels are illustrated in Figures 4-2 to 4-5. Highest levels occur during the day, reflecting the diurnal variation of wind speed, stability and source emission rate as discussed above, but also due to increased traffic activity during the daytime. At the Experimental sites, the highest levels are observed during the afternoon (1200-1800 hrs) period, and this is possibly related to the late afternoon rush hour traffic at these sites (Cannon Street is one-way, going west). The smaller variation at the Control and background sites possibly reflect a more even traffic distribution during the day.

Also observable in these plots is the site to site variability of the data: the Experimental and Control site samplers show similar TSP levels, while the School site is somewhat lower, and the farm and SRC sites are also lower. This diurnal variation in the data is also apparent from modelling results and is shown to be affected by both meteorological and source variations.

Effect of Sampler Position. At the Experimental and Control sites, samplers were positioned at different heights to assess the effects of height above the roadway on TSP levels. In addition, at the Experimental site, the effect of distance from the roadway was also assessed. Figure 5-5 illustrates the effect of height and distance from the roadway. It can be seen that a sharp drop-off in TSP levels occurs within the first 10 m above the roadway at both the Experimental and Control sites. At the Experimental site, a similar drop-off in TSP levels within 30 m distance away from the roadway is also observed. This type of behaviour is observed in all of the TSP data as can be seen by examination of Tables 4-7 to 4-11 and Figures 4-2 to 4-5 for variations in TSP levels from Experimental 1 to Experimental 3, from Control 1 to Control 3 and from Experimental 3 to Experimental 4 and Experimental 6. Differences between these samplers can also be observed in the exceedence data of Table 4-13. This dependence of TSP levels on sampler height and distance from a roadway has been observed elsewhere (241,242) and is almost certainly due to the effect of dust reentrainment from the highway. As shown by the dispersion modelling results, the height profile also contains a component due to the impingement of other area sources.

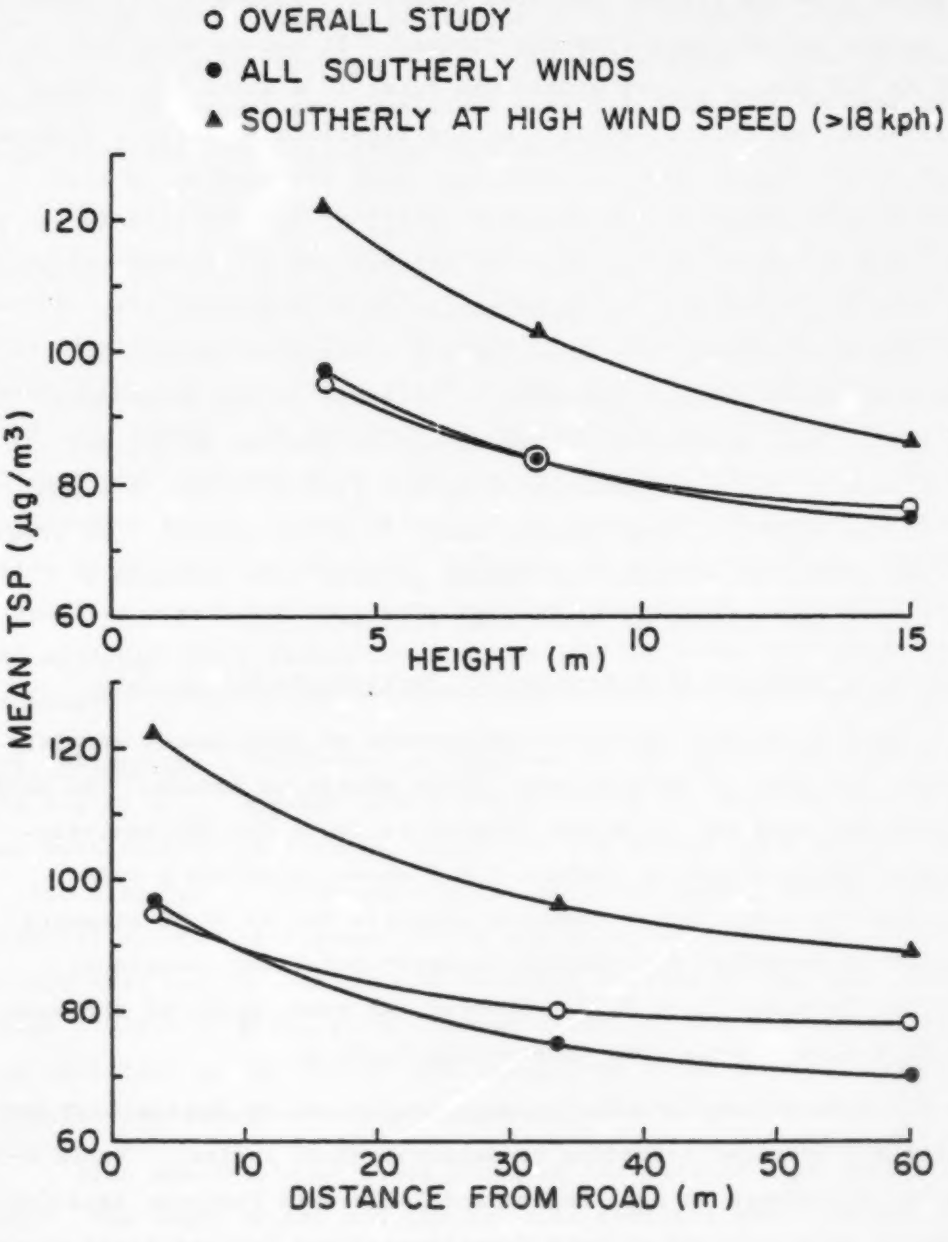
5.1.2 Concentration of Size-Specific Particulate Matter Data

This study was the first application of dichotomous samplers to collect size-specific data on ambient particulate matter in Canada. The main objective of this sampling was to obtain samples suitable for XRF analysis. The XRF technique, as described in Section 3.8.7 above, provides a non-destructive method for quantitative chemical analysis for up to 30 elements, information which is necessary for the CMB receptor modelling technique, described in other Sections (2.6, 5.2). However, an examination of the mass concentration data also reveals some interesting features.

The dichotomous sampler mass loadings are listed in Tables 4-16 and 4-18, subdivided and averaged according to meteorological regime. Table 4-16 contains data for all events in each regime and Table 4-18 contains data for cases where samples were obtained at both Experimental and Control sites during the same period. Except for the $r_3u_2p_1$ regime (northwesterly winds, intermediate wind speeds with precipitation) where only one event was recorded,

FIGURE 5-5

HEIGHT AND DISTANCE PROFILES



the highest levels of fine plus coarse particulate matter are seen for the r_2 regimes (northeasterly winds). This feature is seen in both Table 4-16 and Table 4-18.

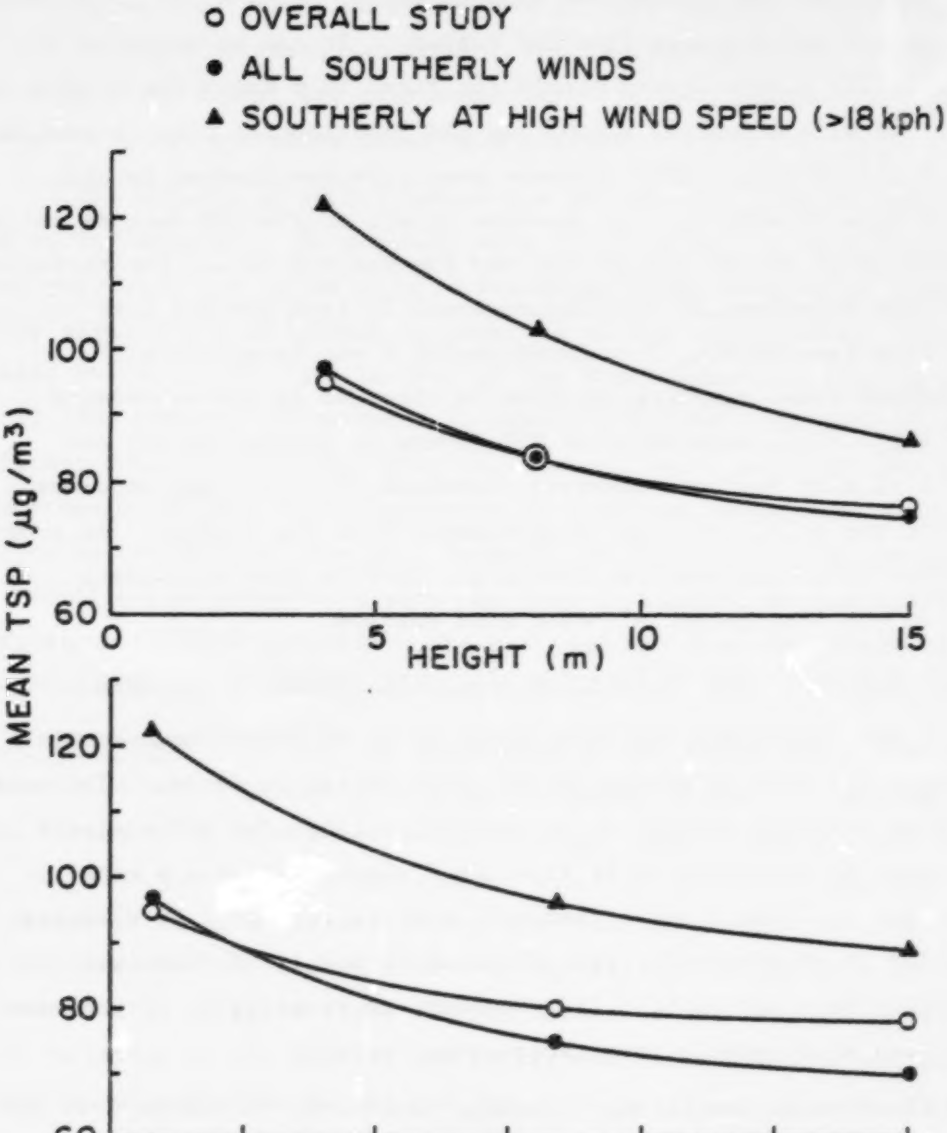
In order to bring out these features of the data without distortions due to too low numbers of samples, the results were averaged for each regime parameter, as presented in Tables 4-17 and 4-19. In Table 4-17, it can be seen that the highest values for fine and coarse particulate matter loadings occur for the r_2 regime, at both the Experimental and Control sites, indicating the effect of industrial emissions to the northeast. This effect can also be observed in Table 4-19 for paired observations. Fine and coarse loadings appear to be approximately equal for winds from any direction at the Experimental site, while there seems to be some lowering of the fine loading relative to the coarse loading at the Control site under northwesterly winds (r_3). The fine fraction is lower under high wind conditions at both sites. The effect of precipitation is to suppress the coarse fraction. Similar effects can be observed in Table 4-19. Overall, the coarse fraction loading is slightly higher than the fine fraction loading.

The ratio of fine to coarse loading, which gives a measure of the size distribution of particulate matter present in the atmosphere, also shows some other features. The ratio is lowest when winds are from the northwest. As secondary aerosols are associated with the fine fractions, this lower ratio implies that such aerosols are not transported into the region from this direction and, as there are no concentrations of industry or urban centres in this sector, an effect of elevated coarse fractions is not occurring. In contrast, the ratio is also lower under high winds or no precipitation conditions, and elevated coarse fractions are probably occurring here. These effects are seen in both Table 4-17 and Table 4-19.

However, the ratio F/(F+C), shows little variation between regimes. Two features are that high wind speeds (u_3) show the lowest ratio because of the presence of more coarse particulate matter in the ambient atmosphere due to wind reentrainment. For periods of precipitation, both the F/C and F/F+C ratios are highest. This is probably because of the suppression effect of precipitation on reentrainment due to particulate wetting, and, to a lesser extent, to the

FIGURE 5-5

HEIGHT AND DISTANCE PROFILES



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The ratio (F+C)/TSP is very consistent under all conditions, except for under northwest winds (r_3) at the Control site where the ratio is quite low. This effect may be due to higher total suspended particulate loadings at this site, compared to other sites because of the proximity of the industrial sector. The overall ratio is around 0.45 which is somewhat lower than the range of 0.6 - 0.7 that has been observed in other urban areas (238). However, the fairly high TSP levels observed probably account for this low ratio. The corresponding ratio of F/TSP is approximately 0.21 overall.

Unfortunately, the dichotomous samplers were not delivered on schedule, and, as a result, there was little time to performance test the instruments before field use. Persistent instrument malfunctions occurred, resulting in substantial data loss especially during the initial segment of the study period. Because of this, temporal evaluation of the size specific particulate data was not possible.

5.1.3 Characterization of Particulate Matter by Chemical and Physical Analysis

Chemical Analyses. To aid in the characterization of the particulate matter, a number of chemical analyses were performed on a selected subset of the samples collected on glass-fibre and cellulose HiVol filters. This resulted in analyses being performed for 36 periods on samples collected on glass-fibre filters at Experimental 1, 3 and 4, Control 1 and 3, School, Farm and SRC sites (288 filters analyzed) and for 106 periods on samples collected on cellulose filters at Experimental 5 and 7 (212 filters analyzed). The samples were selected for analysis according to meteorological regime as outlined in Section 3.8.2. Since the 36 periods selected for glass-fibre filter analysis and the 106 periods selected for cellulose filter analysis only partly overlap, it was felt that averaging by regime parameter would give the most reasonable figures for comparison between sites. Of the parameters analyzed, only nitrate, sulphate, manganese, copper, iron, lead and nickel were consistently present at concentrations above the detection limit. The results of this averaging are tabulated in Appendix K, Tables K1-1 to K1-7.

For nitrate and sulphate, the most striking feature of the data is the general similarity from site to site of the measured concentrations. This implies that nitrate and sulphate species are part of the background aerosol being brought into the Hamilton airshed by long-range transport processes.

For the other elements, no general features can be discerned in the data using this approach. Higher levels of Mn, Fe and Ni are observed at the Cannon Street sites and the School site than at the Farm and SRC sites. This feature can be attributed to the closer proximity of the industrial area. However, no consistent relationship for any of the regime parameters is observed.

Normalized dosage roses were calculated for the seven parameters at each site and are summarized in Appendix K, Tables K2-1 to K2-56. Because the wind rose shows predominant winds from the southwest and northeast quadrants, the dosage roses for each element reflect this bias. As an example of these data, Figure 5-6 illustrates the dosage roses for sulphate at Experimental 3, Control 3, and the three background sites. It can be seen that the roses show predominant sources from the northeast and southwest for the Farm, Experimental 3, and Control 3 sites, whereas the School and SRC sites show predominant sources from the southwest. However, it must be noted that the distribution of winds is affecting the roses almost as much as higher pollutant levels from a particular direction.

Pearson correlation coefficients were calculated between all elements analyzed on glass-fibre filters and the results are summarized in Table 5-2. The only consistently strong correlations are between Mn, Fe, and Ni, between NO_3^- and SO_4^{2-}, and between NH_4^+ and SO_4^{2-}. The metal element correlations are expected because these elements are major constituents of steel industry emissions. The NO_3^-/SO_4^{2-} and NH_4^+/SO_4^{2-} correlations reflect the fact that these ions all are major constituents of secondary aerosols and arise predominantly from a common source, long-range transport.

Tracer Experiment. As described in Section 3.6, the tracer experiment was an attempt to characterize the contribution of dust coming directly from the road by applying a europium chloride solution to the road surface and determining

FIGURE 5-6

Normalized Sulphate Dosage Roses

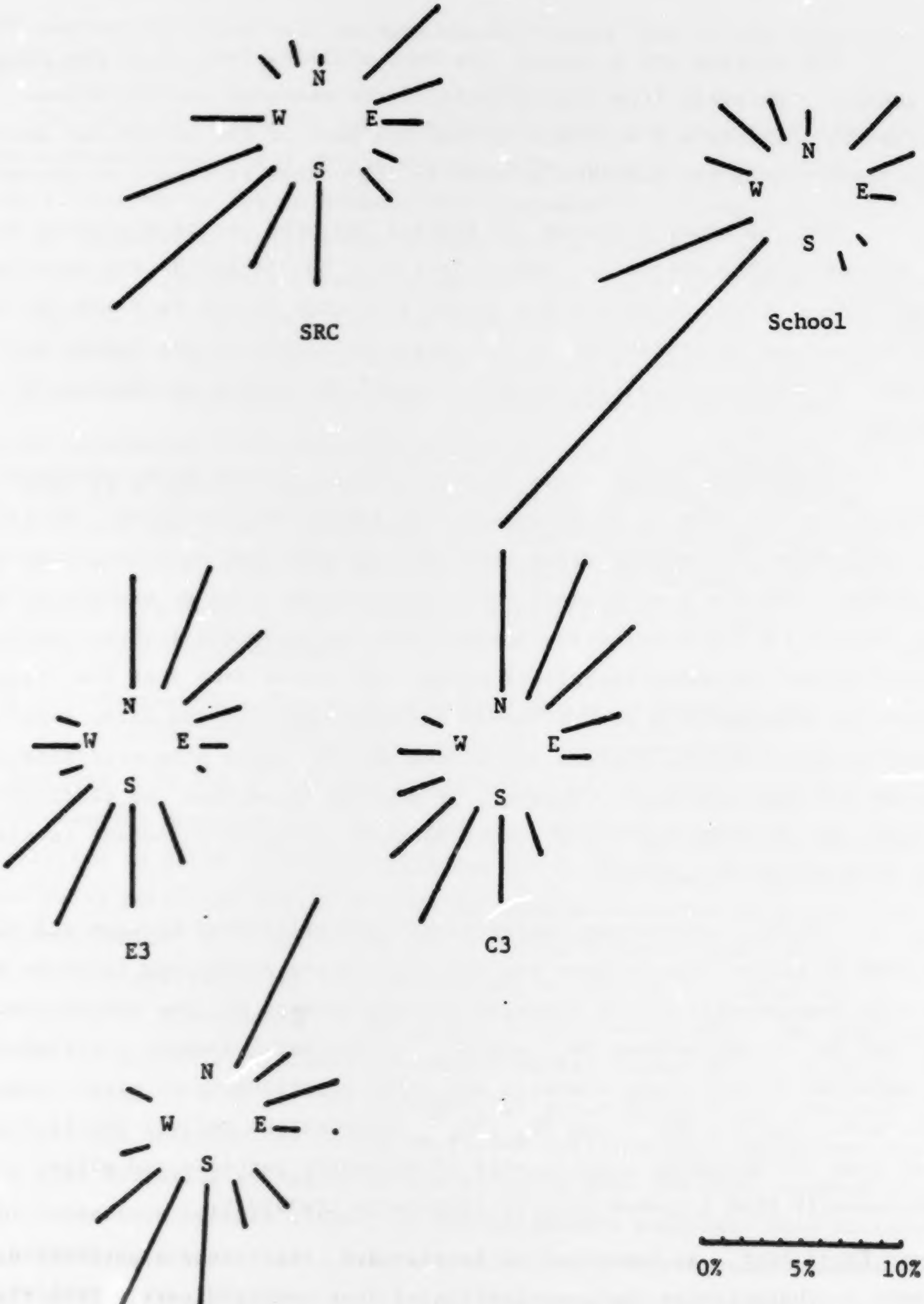


TABLE 5-2

Pearson Correlation Coefficients

Glass-Fibre Filter Analysis Results

WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	0.39	0.23	-0.15	-0.13	-0.19	-0.23	-0.27	0.26	0.02	-0.27	0.08	-0.18	-0.15	-0.29
E3	0.34	0.24	0.12	0.06	-0.14	-0.16	-0.18	-0.03	-0.35	-0.11	0.02	-0.03	0.09	<0.01
E4	0.33	0.22	-0.07	-0.15	-0.11	0.02	-0.19	0.02	-0.20	-<0.01	-0.04	0.01	-0.24	-0.17
C1	0.38	0.19	-0.38	-0.33	-0.20	-0.30	-0.30	-0.31	-0.27	-0.36	-0.21	-0.36	-0.47	-0.37
C3	0.32	0.23	-0.32	-0.09	-0.22	-0.30	-0.13	-0.03	-0.17	-0.16	0.11	-0.32	-0.31	-0.25
School	0.30	0.06	0.32	0.12	-0.07	0.11	0.08	0.28	-0.32	0.05	-0.35	0.17	-0.08	-0.06
Farm	0.27	0.11	-0.02	0.19	-0.14	0.02	-0.20	0.20	0.05	-0.23	-0.19	-0.25	-0.05	-0.24
SRC	0.42	0.06	-0.20	0.20	-0.21	<0.01	0.13	-0.13	0.02	-0.10	-0.08	-0.12	-0.07	-0.38

WD	WS	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	0.39	-0.02	0.05	-0.04	-0.34	-0.21	-0.25	0.31	0.47	-0.36	-0.23	-0.33	-0.05	-0.41
E3	0.34	0.06	-0.18	-<0.01	-0.13	-0.13	0.17	-0.02	-0.26	-0.29	-0.17	-0.15	0.25	-0.16
E4	0.33	-0.06	0.16	-0.12	-0.20	0.14	0.03	0.12	0.39	-0.26	0.22	-0.32	0.02	-0.34
C1	0.38	-0.05	-0.08	-0.30	-0.22	-0.05	-0.19	0.36	0.53	-0.42	-0.29	-0.38	-0.30	-0.42
C3	0.32	<0.01	-0.07	-0.16	-0.25	-0.12	-0.20	0.40	0.13	-0.28	-0.16	-0.49	-0.40	-0.32
School	0.30	0.05	0.10	-0.02	-0.27	0.14	<0.01	0.64	0.18	0.29	0.07	0.32	-0.09	0.16
Farm	0.27	0.03	-0.25	-0.19	-0.30	0.02	-0.07	-0.04	-0.29	-0.02	-0.23	-0.15	0.12	-0.10
SRC	0.42	0.05	-0.10	-0.05	-0.41	-0.15	<0.01	0.27	0.67	-0.19	-0.06	-0.16	-0.13	-0.25

TSP	WS	WD	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	0.23	-0.02	0.29	0.35	0.47	0.37	0.34	-0.37	-0.29	0.32	0.62	0.33	0.02	0.58
E3	0.24	0.06	0.32	0.29	0.36	0.31	0.19	-0.43	0.13	0.35	0.50	0.44	-0.05	0.52
E4	0.22	-0.06	0.27	0.36	0.50	0.20	0.38	-0.21	0.31	0.50	0.08	0.38	0.02	0.50
C1	0.19	-0.05	0.17	0.31	0.43	0.27	0.39	-0.55	0.26	0.19	0.56	0.11	0.04	0.44
C3	0.23	<0.01	0.11	0.30	0.40	0.30	0.39	-0.25	-0.15	0.08	0.26	0.15	0.08	0.29
School	0.06	0.05	0.02	0.01	0.16	0.38	0.38	-0.19	-0.02	0.03	-0.24	0.12	0.16	0.12
Farm	0.11	0.03	-0.14	-0.17	0.03	0.18	-0.01	-0.11	-0.24	-0.07	-0.07	-0.07	-0.19	-0.05
SRC	0.06	0.05	-0.07	0.08	-0.15	-0.12	0.38	0.04	-0.55	-0.01	0.11	0.22	-0.13	0.13

TABLE 5-2 (contd.)

Pearson Correlation Coefficients

K^+	WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	Mn	Cu	Fe	Pb	Ni
E1	0.02	0.48	-0.29	0.58	-0.14	0.07	0.47	0.29	0.27	0.45	0.02	0.52	0.71	0.15
E3	-0.35	-0.26	0.13	0.40	-0.05	0.64	0.38	0.26	0.40	-0.11	-0.57	-0.43	-0.21	-0.17
E4	-0.20	0.39	0.31	0.45	<0.01	0.19	0.10	0.56	-0.17	0.26	0.23	0.07	0.45	0.05
C1	-0.27	0.53	0.26	0.79	0.16	-0.32	0.34	0.29	-0.34	0.52	0.32	0.50	0.43	0.45
C3	-0.17	0.13	-0.15	0.35	-0.47	-0.02	0.24	0.56	0.32	0.81	0.57	0.70	0.46	0.63
School	-0.33	0.18	-0.02	0.61	0.69	-0.03	0.11	0.28	0.04	0.68	0.16	0.65	-0.13	0.19
Farm	0.05	-0.29	-0.24	0.05	-0.02	-0.06	-0.44	0.58	-0.17	0.41	-0.27	0.50	0.23	0.27
SRC	0.02	0.67	-0.55	<0.01	0.43	-0.47	-0.38	-0.49	0.49	0.22	-0.11	-0.06	-0.44	-0.40

Mn	WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Cu	Fe	Pb	Ni
E1	-0.27	-0.36	0.32	0.68	0.05	0.21	0.25	0.21	-0.44	0.45	0.55	0.90	0.46	0.64
E3	-0.11	-0.30	0.35	0.67	0.08	0.07	0.12	0.11	-0.70	-0.11	0.57	0.88	0.26	0.45
E4	<0.01	-0.26	0.50	0.41	-0.07	0.23	-0.08	0.17	-0.51	0.26	<0.01	0.66	0.43	0.29
C1	-0.36	-0.42	0.19	0.79	0.08	0.11	0.31	0.34	-0.79	0.52	0.67	0.96	0.83	0.60
C3	-0.16	-0.28	0.08	0.12	0.03	-0.01	0.02	0.43	-0.44	0.81	0.28	0.72	0.49	0.78
School	0.05	0.29	0.03	0.46	0.40	-0.08	0.16	<0.01	-0.21	0.68	-0.12	0.95	0.31	0.44
Farm	-0.23	-0.02	-0.07	0.60	0.42	0.45	0.22	0.50	-0.25	0.41	0.01	0.90	0.78	0.74
SRC	-0.10	-0.19	-0.01	-0.11	+0.12	-0.11	-0.22	-0.05	-0.20	-0.22	0.25	0.94	0.40	0.43

Cu	WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Fe	Pb	Ni
E1	0.08	-0.23	0.62	0.49	< 0.01	0.44	0.19	0.24	-0.35	0.02	0.55	0.63	0.22	0.60
E3	0.02	-0.17	0.50	0.66	0.15	0.13	0.11	0.19	-0.68	-0.57	0.57	0.67	0.18	0.60
E4	-0.04	0.22	0.08	0.08	0.04	-0.09	-0.22	-0.02	-0.52	0.23	<0.01	-0.04	0.27	0.02
C1	-0.21	-0.29	0.56	0.58	0.31	0.43	0.30	0.40	-0.88	0.32	0.67	0.59	0.56	0.69
C3	0.11	-0.16	0.27	0.13	0.15	0.16	0.07	0.24	-0.32	0.57	0.28	0.35	0.24	0.37
School	-0.35	0.07	-0.24	-0.32	-0.01	-0.03	<0.01	-0.39	-0.39	0.16	-0.12	-0.12	-0.20	0.11
Farm	-0.19	-0.23	-0.07	0.25	-0.17	0.13	0.04	0.16	-0.54	-0.27	0.01	0.03	0.08	0.25
SRC	-0.08	-0.06	0.11	-0.13	0.12	-0.14	-0.18	0.11	0.73	-0.11	0.24	0.32	-0.16	0.43

TABLE 5-2 (contd.)

Pearson Correlation Coefficients

Fe	WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Pb	Ni
E1	-0.18	-0.32	0.33	0.61	0.05	0.29	0.30	0.32	-0.47	0.52	0.90	0.63	0.40	0.61
E3	-0.03	-0.15	0.44	0.70	0.12	0.17	0.19	0.26	-0.77	-0.43	0.88	0.67	0.15	0.51
E4	0.01	-0.32	0.38	0.59	-0.06	0.21	0.04	0.15	-0.68	0.07	0.66	-0.04	0.38	0.33
C1	-0.36	-0.38	0.11	0.77	0.09	0.11	0.03	0.02	-0.68	0.43	0.96	0.59	0.77	0.53
C3	-0.32	-0.49	0.15	0.56	0.06	0.12	0.24	0.60	-0.38	0.70	0.72	0.35	0.77	0.81
School	0.17	0.32	0.12	0.54	0.40	-0.02	0.22	0.14	-0.12	0.65	0.95	-0.12	0.34	0.52
Farm	-0.25	-0.15	-0.07	0.55	0.28	0.43	0.28	0.54	-0.13	0.50	0.90	0.03	0.60	0.75
SRC	-0.12	-0.16	0.02	-0.08	0.02	-0.15	-0.24	<0.01	0.11	-0.06	0.94	0.32	0.43	0.50

Pb	WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Ni
E1	-0.15	-0.05	0.02	0.37	0.07	-0.16	-0.22	<0.01	-0.22	0.71	0.46	0.22	0.40	0.19
E3	0.09	0.25	-0.05	0.06	-0.04	-0.43	-0.32	-0.34	-0.11	-0.21	0.26	0.18	0.15	0.08
E4	-0.24	0.02	0.02	0.23	0.02	-0.19	-0.19	-0.09	-0.45	0.45	0.43	0.27	0.38	0.02
C1	-0.47	-0.30	0.04	0.61	-0.10	-0.25	0.03	0.02	-0.49	0.43	0.83	0.56	0.77	0.46
C3	-0.31	-0.40	0.08	0.46	-0.28	-0.15	0.18	0.32	-0.23	0.46	0.49	0.24	0.77	0.54
School	-0.08	-0.09	0.16	0.11	-0.10	0.33	0.32	0.36	0.09	-0.13	0.31	-0.20	0.34	0.32
Farm	-0.05	0.12	-0.18	0.74	0.46	0.30	0.15	0.43	-0.42	0.23	0.78	0.08	0.60	0.50
SRC	-0.07	-0.13	-0.13	0.22	0.06	0.23	0.21	0.08	0.20	-0.44	0.40	-0.16	0.44	0.30

Ni	WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Pb
E1	-0.29	-0.41	0.58	0.46	0.51	0.47	0.33	0.36	-0.68	0.15	0.64	0.60	0.61	0.19
E3	<0.01	-0.16	0.52	0.25	0.76	0.10	<0.01	0.31	-0.66	-0.17	0.45	0.60	0.51	0.08
E4	-0.17	-0.34	0.50	0.26	0.65	0.33	-0.02	0.23	-0.68	0.05	0.29	0.02	0.33	0.02
C1	-0.37	-0.42	0.44	0.62	0.58	0.39	0.31	0.43	-0.91	0.45	0.60	0.69	0.53	0.46
C3	-0.25	-0.32	0.29	0.27	0.51	0.17	0.11	0.55	-0.60	0.63	0.78	0.37	0.80	0.54
School	-0.06	0.16	0.12	0.29	0.42	0.35	0.45	0.42	-0.29	0.19	0.44	0.11	0.52	0.32
Farm	-0.24	-0.10	-0.05	0.40	0.28	0.62	0.41	0.63	0.02	0.27	0.74	0.25	0.75	0.50
SRC	-0.38	-0.25	0.12	-0.09	0.25	0.46	0.30	0.36	0.55	-0.40	0.43	0.43	0.50	0.30

TABLE 5-2 (contd.)

Pearson Correlation Coefficients

SO_4^{2-}	WS	WD	TSP	Cl^-	Br^-	NO_3^-	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	-0.23	-0.21	0.37	0.16	0.03	0.73	0.89	0.63	0.47	0.25	0.19	0.30	-0.22	0.33
E3	-0.16	-0.13	0.31	0.08	-0.09	0.66	0.62	0.74	0.38	0.12	0.11	0.19	-0.32	<0.01
E4	0.02	0.14	0.20	0.03	0.22	0.29	0.57	0.72	0.10	-0.08	-0.22	0.04	-0.19	-0.02
C1	-0.30	-0.05	0.27	0.49	0.22	0.66	0.95	0.63	0.34	0.31	0.30	0.34	0.03	0.31
C3	-0.30	-0.12	0.30	0.51	0.23	0.63	0.58	0.68	0.24	0.02	0.07	0.24	0.18	0.11
School	0.11	0.14	0.38	0.38	0.23	0.75	0.54	0.74	0.11	0.16	<0.01	0.22	0.32	0.45
Farm	0.02	0.02	0.18	0.39	0.18	0.68	0.65	0.52	-0.44	0.22	0.04	0.28	0.15	0.41
SRC	<0.01	-0.15	-0.12	0.05	0.30	0.75	0.69	-0.82	-0.38	-0.22	-0.18	-0.24	0.21	0.30

Na^+	WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	NH_4^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	-0.27	-0.25	0.34	0.05	0.11	0.82	0.89	0.16	0.29	0.22	0.24	0.32	<0.01	0.36
E3	-0.18	-0.17	0.16	0.03	-0.17	0.52	0.62	-0.17	0.26	0.11	0.19	0.26	-0.34	0.31
E4	-0.19	0.03	0.38	0.15	0.21	0.79	0.57	0.30	0.56	0.17	-0.03	0.15	-0.09	0.23
C1	-0.30	-0.19	0.39	0.54	0.26	0.79	0.95	0.26	0.29	0.34	0.40	0.35	0.02	0.43
C3	-0.12	-0.20	0.39	0.57	0.14	0.56	0.58	-0.40	0.57	0.43	0.24	0.60	0.32	0.54
School	0.08	<0.01	0.38	0.33	0.35	0.55	0.54	0.52	0.28	<0.01	-0.39	0.14	0.36	0.42
Farm	-0.20	-0.07	-0.01	0.24	0.30	0.62	0.65	-0.17	0.58	0.50	0.12	0.54	0.43	0.63
SRC	0.13	<0.01	0.38	-0.13	0.22	0.45	0.69	-0.11	0.49	-0.05	0.11	<0.01	0.08	0.36

NH_4^+	WS	WD	TSP	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	0.26	0.31	-0.37	-0.17	-0.44	0.10	0.63	0.16	0.27	-0.44	-0.36	-0.47	-0.23	-0.68
E3	-0.03	0.02	-0.43	0.52	-0.42	0.60	0.74	-0.16	0.40	-0.70	-0.68	-0.77	-0.11	-0.66
E4	0.02	0.12	-0.21	-0.23	-0.31	-0.07	0.72	0.30	-0.17	-0.51	-0.52	-0.68	-0.45	-0.68
C1	-0.31	0.36	-0.55	-0.62	-0.50	-0.05	0.63	0.26	-0.34	-0.79	-0.88	-0.68	-0.49	-0.91
C3	-0.03	0.40	-0.24	0.02	-0.35	0.31	0.68	-0.40	0.32	-0.44	-0.33	-0.38	-0.23	-0.60
School	0.28	0.64	-0.19	0.51	-0.12	0.21	0.74	0.52	0.04	-0.21	-0.40	-0.12	0.09	-0.29
Farm	0.20	-0.04	-0.11	-0.73	-0.24	-0.33	0.52	-0.17	-0.17	-0.25	-0.54	-0.13	-0.42	0.02
SRC	-0.13	0.27	0.04	-0.10	0.24	-0.67	-0.82	-0.11	0.49	-0.20	0.73	0.11	0.20	0.55

TABLE 5-2 (contd.)

Pearson Correlation Coefficients

Cl^-	WS	WD	TSP	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	-0.15	0.05	0.29	0.14	0.03	0.16	0.05	-0.17	0.58	0.68	0.49	0.61	0.37	0.46
E3	0.12	-0.18	0.32	<0.01	0.02	0108	0.03	0.52	-0.40	0.67	0.66	0.70	0.06	0.25
E4	-0.07	0.16	0.27	-0.15	0.06	0.03	0.15	-0.23	0.45	0.41	0.08	0.59	0.23	0.26
C1	-0.38	-0.08	0.17	0.22	0.16	0.49	0.54	-0.62	0.79	0.79	0.58	0.77	0.61	0.62
C3	-0.32	-0.07	0.11	<0.01	0.15	0.51	0.57	0.02	0.35	0.12	0.13	0.55	0.46	0.27
School	0.32	0.10	0.02	0.26	0.18	0.38	0.33	0.51	0.61	0.46	-0.32	0.54	0.11	0.29
Farm	-0.02	-0.25	-0.14	0.09	0.36	0.39	0.24	-0.73	0.05	0.60	0.25	0.55	0.74	0.40
SRC	-0.20	-0.10	-0.07	-0.07	-0.06	0.05	-0.13	-0.10	<0.01	-.11	-0.13	-0.08	0.22	-0.09

Br^-	WS	WD	TSP	Cl^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	-0.13	-0.04	0.35	0.14	<0.01	0.03	0.11	-0.44	-0.14	0.05	<0.01	0.05	0.07	0.51
E3	0.06	-<0.01	0.29	<0.01	-0.03	-0.09	-0.17	-0.42	-0.05	0.08	0.15	0.12	-0.04	0.76
E4	-0.15	-0.12	0.36	-0.15	0.14	0.22	0.21	-0.31	<0.01	-0.07	0.04	-0.06	0.02	0.65
C1	-0.33	-0.30	0.31	0.22	0.35	0.22	0.26	0.50	0.16	0.08	0.31	0.09	-0.10	0.58
C_3	-0.09	-0.16	0.30	<0.01	0.28	0.23	0.14	-0.35	-0.47	0.03	0.15	0.06	0.11	0.51
School	0.12	-0.02	0.01	0.26	0.22	0.23	0.35	-0.12	0.69	0.40	-0.01	0.40	-0.10	0.42
Farm	0.19	-0.19	-0.17	0.09	0.44	0.18	0.30	-0.24	-0.02	0.42	-0.17	0.28	0.46	0.28
SRC	0.20	-0.05	0.08	-0.07	0.38	0.30	0.22	0.24	-0.44	0.12	0.12	0.02	0.06	0.25

NO_3^-	WS	WD	TSP	Cl^-	Br^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mn	Cu	Fe	Pb	Ni
E1	-0.19	-0.34	0.47	0.03	<0.01	0.73	0.82	0.10	0.07	0.21	0.44	0.29	-0.16	0.47
E3	-0.14	-0.13	0.36	0.02	-0.03	0.66	0.51	0.60	0.64	0.07	0.13	0.17	-0.44	0.10
E4	-0.11	-0.20	0.50	0.60	0.14	0.29	0.79	-0.07	0.19	0.23	-0.09	0.21	-0.19	0.33
C1	-0.20	-0.22	0.43	0.16	0.35	0.66	0.79	-0.05	-0.32	0.11	0.43	0.11	-0.25	0.39
C3	-0.22	-0.25	0.40	0.15	0.28	0.63	0.56	0.31	-0.02	-0.01	0.16	0.12	-0.15	0.17
School	0.07	-0.27	0.16	0.18	0.22	0.75	0.55	0.21	-0.03	-0.08	-0.03	-0.02	0.33	0.35
Farm	-0.14	-0.30	0.03	0.36	0.44	0.68	0.62	-0.33	-0.06	0.45	0.13	0.43	0.30	0.62
SRC	-0.21	-0.41	-0.15	-0.06	0.38	0.75	0.45	-0.67	-0.47	-0.11	-0.14	-0.15	0.23	0.46

the europium (Eu) concentration at the Experimental 7 and Experimental 5 HiVol sampling sites. A plot of Eu concentration versus period after application is illustrated in Figure 5-7 for both sampling locations. It can be seen that the Eu concentration is initially high and decays down to background levels in about 36 hours. The slight rise in Eu concentration 24 hours after application is probably due to increased traffic during the morning rush hour. Figure 5-7a shows the data for Experimental 7, situated 3 m from the road (4 m height) and Figure 5-7b shows the data from Experimental 5, situated 33 m from the road (4 m height).

From the relative Eu concentrations at the two sites, it can be deduced that the road dust contribution to suspended particulate levels falls off with distance from the road. This dependence can be used to deduce the road dust contribution to TSP or other parameters using the assumption that all Eu detected is from the tracer application. The ratio Eu (E7)/Eu(E5) averages approximately 5 for the first 24 hours after application. Also, the study mean TSP at Experimental 3 (adjacent to Experimental 7) was 96 $\mu g/m^3$ and at Experimental 4 (adjacent to Experimental 5) was 80 $\mu g/m^3$. The measured TSP can be assumed to have a road dust component, TSP (r) and a component due to all other sources, TSP (os), such that:

$$\text{TSP (r)} + \text{TSP (os)} = \text{TSP (meas)}$$

Then, using the figures above, two simultaneous equations can be written:

at E3/7, $\text{TSP (r)} + \text{TSP (os)} = 96\ \mu g/m^3$

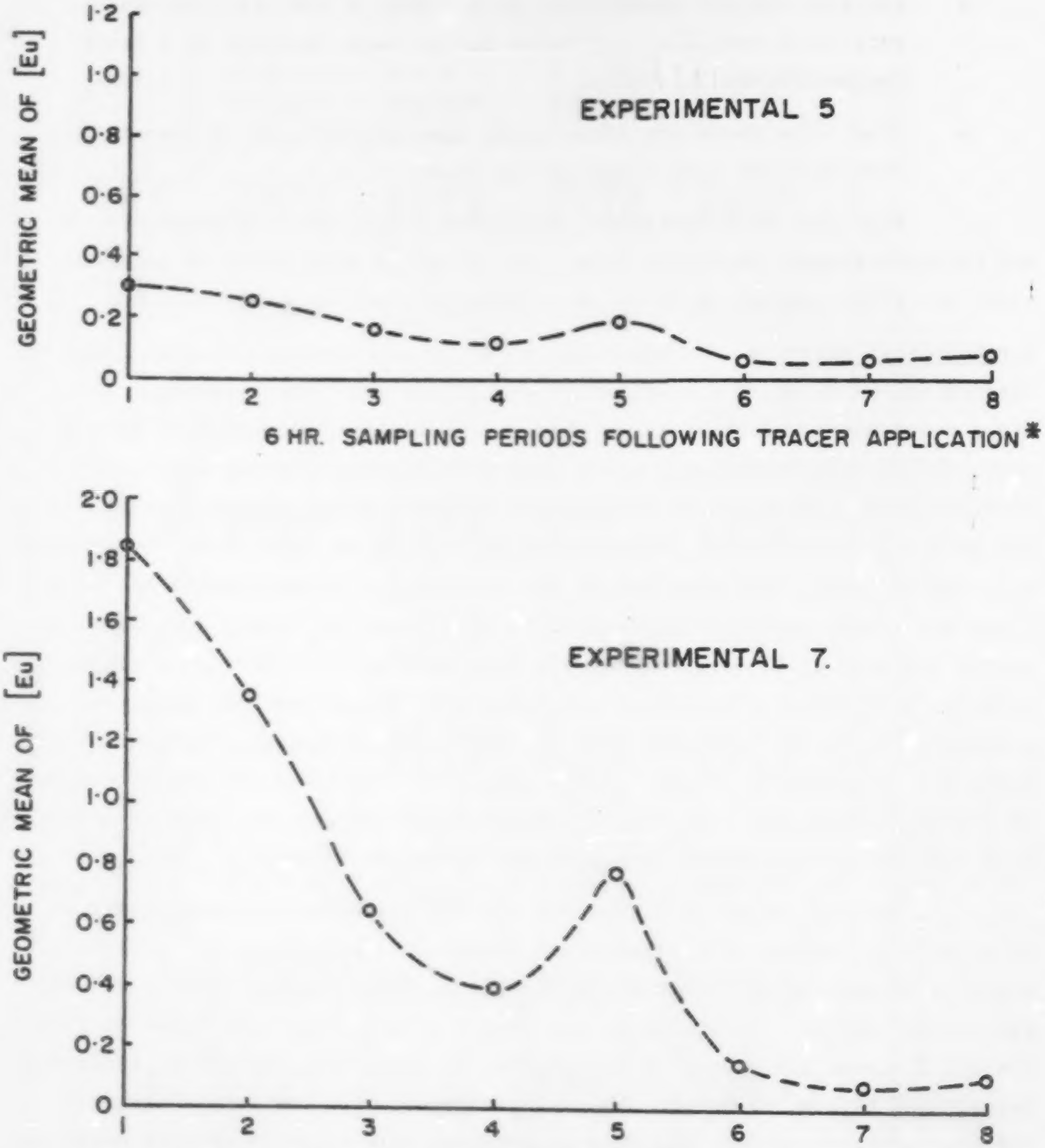
at E4/5, $0.2\ \text{TSP (r)} + \text{TSP (os)} = 80\ \mu g/m^3$

Thus, by difference, $0.8\ \text{TSP (r)} = 16\ \mu g/m^3$

and $\text{TSP (r)} = \frac{16}{0.8} = 20\ \mu g/m^3$

Thus, from this approach, approximately 20 $\mu g/m^3$ of TSP is attributable to road dust from the immediately adjacent roadway, a figure that is in general agreement with the modelling results discussed later.

This approach shows considerable promise as a technique for future use when it is desired to identify the contribution of a specific source to TSP loadings. A more quantitative interpretation of the data obtained in this study was not attempted for the following reasons:



* TRACER APPLIED DURING THE FIRST PERIOD

FIGURE 5·7 GEOMETRIC MEAN OF [Eu] vs TIME FOR ALL APPLICATIONS

- the wind regimes experienced during many of the applications were quite variable, and hence may not have resulted in a truly representative Eu profile
- other area roads are shown to be important sources of reentrained dust by other components of the study.

With further refinements, including a more detailed assessment of the Eu reentrainment mechanism (i.e., Eu/TSP ratio, dependence on particle size, etc.) this method could be of considerable use in future studies.

Morphological Analysis. As described in Section 3, morphological analysis was carried out on a set of filters selected to represent sites forming a line along a southwest -northeast axis through the Hamilton study area. Samples collected in conjunction with winds from both the southwest and northeast were analyzed. The detailed results are included in Appendix G, Tables G6-1 and G6-2 and the following general observations can be made. For the samples analyzed when the winds were out of the southwest, the Farm sample was quite clean and showed deposits characteristic of a "country" sample (i.e., pollen, starch and biological debris). At the Experimental 3 and Control 3 sites, evidence of industrial emissions was seen, with flyash and coal particles being observed. At the School site, more of these same industrial components were detected. All samples showed calcite, which is ubiquitous and characteristic of soil, limestone and road dust (although these sources are indistinguishable) with the downtown and School samples showing larger deposits of calcite.

When the winds were from the northeast, the School site showed relatively low levels of virtually all components, similar to the Farm site above, with some pollen, starch and biological debris characteristic of rural particulate matter. In addition, the Cannon Street sites, Experimental 3 and Control 3 showed components characteristic of industrial emissions, including deposits of flyash, haematite and coal particles, with one sample having a catalyst particle on it. The Farm site showed some evidence of both rural and industrial deposits. The general conclusions are similar to those arrived at for the TSP data above, indicating the strong wind direction dependence of industrial emissions in the Hamilton area.

The samples were also chemically analyzed for a range of parameters. These results are presented in Table 5-3. It can be seen that the results are

TABLE 5-3

Summary of Chemical Analyses for Filters Evaluated by Optical Microscopy

	µg/m³				ng/m³						
	TSP	NO_3^-	$SO_4^=$	Al	Mn	Fe	Cu*	Zn	Pb	V	Ti
June 19, 6-12, NE Winds											
School	47	1.9	3.3	23.3	66	1605	289	<64	215	7.6	29
Expt. 3	82	1.2	4.4	32.6	164	3054	70	121	769	10.9	87
Cont. 3	190	2.0	9.2	17.7	497	10693	48	798	1346	81.7	158
Farm	45	0.9	3.9	16.7	159	1998	22	86	231	7.7	36
June 27, 12-18, SW Winds											
School	159	4.0	19.1	66.4	367	7196	127	694	680	26.8	88
Expt. 3	242	4.2	12.0	48.0	302	6319	99	385	1612	26.4	152
Cont. 3	150	4.0	12.0	49.1	233	3740	48	367	1080	21.9	80
Farm	77	2.7	14.4	30.4	42	961	20	356	155	8.1	60
Aug. 21, 6-12, NE Winds											
School	70	5.8	7.5	26.1	29	1353	138	680	815	14.8	18
Expt. 3	137	3.2	11.0	39.5	264	4521	72	576	1773	27.3	137
Cont. 3	272	3.4	13.0	37.8	5873	20116	105	1003	2892	110.0	272
Farm	125	3.8	12.6	30.4	624	7155	43	709	982	28.6	125
Aug. 25, 12-18, SW Winds											
School	122	2.8	8.1	23.1	371	6914	39	589	413	16.6	34
Expt. 3	101	2.9	5.7	30.5	105	2011	48	118	691	9.1	76
Cont. 3	68	2.9	5.7	44.6	88	1269	27	340	583	13.5	39
Farm	46	2.6	5.6	30.7	27	377	10	280	71	4.6	25

*Copper analyses of HiVol samples must be interpreted with caution because of the possibility of self-contamination by the sampler motor.

qualitatively in agreement with the above conclusions, although no consistent pattern between sites is evident.

Other Parameters. At the time the study was planned, it was thought that CO and COH data would shed some light on the interaction between traffic levels, reentrained road dust and TSP levels. However, in the course of data analysis, it became apparent that these data were not as useful as originally believed and so these data have not been analyzed in any detail.

The traffic data summarized in Tables 4-24 and 4-25 for the Experimental and Control sites indicate that the traffic volume is relatively constant throughout the week and lower on weekends, with daily traffic levels being highest during the afternoon rush hour. This latter observation is consistent with Cannon Street being one-way westbound, thus serving as a major arterial route away from the industrial area.

The results from the sieve analysis of the road dust collected from the street surface indicate that approximately 5% of the dust on the street is in the reentrainable (< 37 μm) size range. This is consistent with the results of other studies (215,243). The dustfall data indicate that dustfall levels were higher in July than August at both Experimental and Control sites, in agreement with the TSP data. Also, the two sites show similar levels.

Carbon analyses were carried out on a number of filters. The object of these analyses was to identify the contribution of carbon species to the TSP loadings, and, through comparisons with CMB data, to identify their sources. From the data in Tables 5-4 and 5-5, it is apparent that carbon makes a substantial contribution to TSP levels. Levels vary from 2 $\mu g/m^3$ to 30 $\mu g/m^3$, representing from 5 to 25% of the TSP. Generally, the carbon is evenly divided between organic and inorganic carbon species.

5.2 Identification of Major Sources

Several recent studies which have been undertaken to characterize and identify sources of particulate matter have been reported and these are reviewed in Section 2.4. It is apparent from this review that the quantitative source apportionment of particulate matter in an urban area is very difficult. Several methods are available but each method suffers from various weaknesses.

TABLE 5-4

Carbon Analysis Results - Experimental 3

($\mu g/m^3$)

Sample Period	Met. Regime	TSP	Organic Carbon	Elemental Carbon	Total Carbon
77	$r_2u_1P_1$	92	4.27 ± 1.31	6.11 ± 1.02	10.38 ± 1.04
80	$r_3u_1P_1$	153	12.18 ± 1.76	14.78 ± 2.49	26.96 ± 2.70
83	$r_1u_2P_1$	39	0.37 ± 1.24	1.39 ± 0.37	1.76 ± 0.18
86	$r_1u_1P_1$	54	3.00 ± 1.26	3.74 ± 0.70	6.74 ± 0.67
102	$r_1u_1P_2$	46	3.37 ± 1.26	3.53 ± 0.64	6.90 ± 0.69
107	$r_1u_1P_2$	72	8.25 ± 1.45	4.94 ± 0.97	13.19 ± 1.32
120	$r_1u_3P_1$	142	11.40 ± 1.64	11.38 ± 1.81	22.78 ± 2.28
189	$r_1u_1P_2$	142	9.93 ± 1.55	7.78 ± 1.43	17.80 ± 1.78
209	$r_2u_1P_1$	112	9.63 ± 1.57	9.71 ± 1.71	19.34 ± 1.93
210	$r_2u_1P_1$	73	4.23 ± 1.31	8.56 ± 1.32	12.79 ± 1.28
215	$r_1u_2P_2$	142	18.09 ± 2.11	14.27 ± 2.43	32.35 ± 3.24
228	$r_2u_2P_2$	100	8.92 ± 1.50	8.96 ± 1.55	17.87 ± 1.79
232	$r_1u_3P_2$	318	24.91 ± 2.63	16.94 ± 2.87	41.84 ± 4.18

Regime Definitions (Figure 3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	P_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	P_2 = none
r_3 = SW Sector	u_3 = > 18 km/hr	

TABLE 5-5

Carbon Analysis Results - Control 3

($\mu g/m^3$)

Sample Period	Met. Regime	TSP	Organic Carbon	Elemental Carbon	Total Carbon
77	$r_2u_1p_1$	92	12.74 ± 1.80	12.74 ± 2.16	25.48 ± 2.55
80	$r_3u_1p_1$	153	16.86 ± 2.18	19.27 ± 3.29	36.13 ± 3.61
83	$r_1u_2p_1$	39	1.23 ± 1.25	1.53 ± 0.44	2.76 ± 0.28
86	$r_1u_1p_1$	54	4.43 ± 1.31	4.02 ± 0.75	8.45 ± 0.84
102	$r_1u_1p_2$	46	4.39 ± 1.31	2.17 ± 0.62	6.56 ± 0.66
107	$r_1u_1p_2$	72	13.54 ± 1.75	6.64 ± 1.31	20.17 ± 2.02
120	$r_1u_3p_1$	142	14.86 ± 1.96	7.55 ± 1.82	22.40 ± 2.24
189	$r_1u_1p_1$	142	16.39 ± 2.06	8.92 ± 2.07	25.30 ± 2.53
209	$r_2u_1p_1$	112	10.53 ± 1.60	13.29 ± 2.16	23.82 ± 2.38
210	$r_2u_1p_1$	73	1.32 ± 1.25	7.03 ± 1.12	8.35 ± 0.84
215	$r_1u_2p_2$	142	12.81 ± 1.73	11.22 ± 1.89	24.03 ± 2.40
228	$r_2u_2p_2$	100	9.95 ± 1.56	8.03 ± 1.45	17.98 ± 1.80
232	$r_1u_3p_2$	318	19.91 ± 2.34	9.14 ± 2.33	29.05 ± 2.91

Regime Definitions (Figure 3-24)

Wind Dir.	Wind Speed	Pptn.
r_1 = SW Sector	u_1 = < 8 km/hr	p_1 = some
r_2 = NE Sector	u_2 = 9-18 km/hr	p_2 = none
r_3 = SW Sector	u_3 = > 18 km/hr	

Thus, a source apportionment study must rely on the use and comparison of several methodologies in order to derive a reasonable and reliable semi-quantitative source apportionment.

In addition to the general features of airborne particulate concentration data (particularly wind and pollution roses as discussed in Section 5.1), the specific techniques of the microinventory, dispersion modelling, and chemical mass balance (CMB) were used in this study. These three methods and their results are discussed in this Section.

5.2.1 Microinventory

The methodology and results of the microinventory have been given in Sections 3.2 and 4.1, respectively. The method can be best described as a semi-empirical predictive receptor model which identifies the expected TSP (annual geometric mean) at a given site as well as the contribution to that TSP by area, point, local (immediate vicinity traffic related), and background or "city effect" source categories.

In calculating the expected TSP at a given receptor site, each source category emission figure is weighted by a coefficient determined from a regression equation. Using the observed TSP levels at the 13 sites during the study period and the calculated emission figures for application to the regression equation (see Table 4-1), a Hamilton-specific regression equation can be derived. The summary statistics for this equation are presented in Table 4-3, and the resulting calculated TSP, along with the contributions from the area, point and local sources, are listed in Table 4-5 for each site. The microinventory technique is based on the use of annual emission factors to calculate annual TSP levels. However, since the period of this study covered only three summer months and the summer traditionally has higher TSP levels in Hamilton, the measured average TSP at the 13 sites should be adjusted to reflect expected annual geometric means. These data were adjusted to expected annual values using scaling factors derived from MOE HiVol data as described in Section 4-1. From these data, an annually adjusted Hamilton-specific regression equation was derived. The summary statistics are presented in Table 4-4 and the resulting calculated TSP, along with the contributions from the area, point and local sources, are listed in Table 4-6 for each site.

As discussed in Section 4.1, a third general regression equation which can be used is that developed by Pace (51) using data collected at 79 sites located in several U.S. cities, some of which have a similar climatology to Hamilton. This equation was applied to several other locations in different cities not used in the development of the regression equation and the results were found to correlate extremely well with measured TSP values. The levels predicted for the Hamilton area by this equation are summarized in Table 4-2 and the summary statistics are shown below:

Variable	Coefficient	Std. Error
Area	0.451E-02	0.82E-03
Point	0.96E-3	0.14E-03
Local	50.5	12.0

Thus, there are three different regression equations which can be used to determine TSP values at the receptor sites: the Pace equation, the Hamilton-specific equation and the annual adjusted Hamilton-specific equation. All three equations produce reasonably good correlations between observed and predicted TSP levels (better than about ± 11 $\mu g/m^3$). However, the uncertainty in the source component coefficients is relatively large for both Hamilton equations. The relative percent standard errors are summarized below:

Variable	Pace Equation	Hamilton-Specific Equation	Hamilton Annually Adjusted Specific Equation
Area	18	58	132
Point	15	32	23
Local	24	13	16

Of the two Hamilton-specific equations, the derivation based upon annually adjusted TSP levels is the most appropriate to consider, since the microinventory involves annual average emission rates. Unfortunately, two factors contribute to the uncertainty of this derivation:

- measurements from only 13 sites were used, compared with 79 sites in the earlier derivations by Pace (51).
- 10 of the 13 monitoring sites were clustered in a relatively small geographic area in which the impact of area and point contributions could be expected to show little variability.

Furthermore, the Pace equation has been shown to produce good results in cities other than those in which it was derived, and is based on actual measured annual geometric TSP means, whereas the Hamilton data were not available for a full period of one year. For these reasons, the Pace equation is felt to be more reliable, but the Hamilton annually adjusted results are also of interest, since they are more specific to the study area.

The results of the microinventory calculations using both the Pace equation and the Hamilton-specific equation are summarized in Table 5-6. Annually adjusted observed TSP levels are plotted against the values predicted by the Pace equation in Figure 5-8.

The predicted and measured values are in very good agreement except for the School and Farm sites with the Pace equation for which the predicted values are approximately 40% and 30% low, respectively. This may be due to an underestimate in the area source component resulting from reentrained dust from the beach strip for the School and reentrainment of dust from nearby agricultural fields for the Farm.

For both equations, the "city effect" or background term is significant, ranging from over 90% of the predicted TSP at SRC and the Farm, to a minimum of 32% at the Oak Street site.

Several components of this "city effects" term have been distinguished by Pace (51). The largest component is probably background, that portion of ambient concentrations which cannot be reduced by controlling emissions from local man-made sources. Background, in turn, has many components, including wind-blown dust from natural surfaces, biological debris, and long-range transport of both primary and secondary aerosols.

Two other probable components of this term have been described by Pace as "urban excess", in that the components are not accounted for in a measured non-urban background concentration. The first of these is locally emitted sulphur and nitrogen gases and organics that form secondary aerosols in the atmosphere. The other component is the collective impact of area and small point sources located in the urban area but outside the one mile radius microinventory area. Since the impacts of the above sources vary considerably from city to city but to a much smaller degree for different sites within the same urban area, the constant also varies depending on the city being studied.

TABLE 5-6

Microinventory Results Using (a) the Pace Equation and (b) the Hamilton-Specific Equation (Annually Adjusted)

Site	Microinventory Contributions (μg/m^3)[a]				Measured[c] Total	Microinventory Contributions (μg/m^3)[b]			
	Area	Point	Local	Total		Total	Area	Point	Local
Expt. 1	19	2	11	64	65	69	2	14	9
Expt. 2	24	2	18	76	71	75	3	14	14
Expt. 3	36	2	26	96	81	82	4	14	20
Expt. 4	36	2	7	77	68	68	4	14	6
Expt. 6	36	2	5	75	66	65	4	14	3
Control 1	14	2	14	62	70	70	2	13	11
Control 2	16	2	21	71	75	75	2	13	16
Control 3	24	2	31	89	84	83	3	13	23
John St.	30	2	31	95	93	82	3	12	23
Oak St.	25	2	43	101	89	94	3	14	33
School	8	5	0	45	75	72	1	27	0
Farm	3	0	0	35	50	44	< 1	0	0
SRC	5	0	0	37	40	45	1	< 1	0

(a) Calculated according to Pace regression equation:
TSP (geom. mean) = 0.00451 (Area) + 0.00096 (Point) + 50.5 (Local) + 32 ± 11 μg/m^3
($r = 0.876$, $r^2 = 0.767$)

(b) Calculated according to Hamilton-specific Equation using Annually Adjusted TSP Levels:
TSP (geom. mean) = 0.000497 (Area) + 0.00591 (Point) + 37.9 (Local) + 44.35 ± 5 μg/m^3
($r = 0.955$, $r^2 = 0.882$)

(c) Annually Adjusted Geometric Means

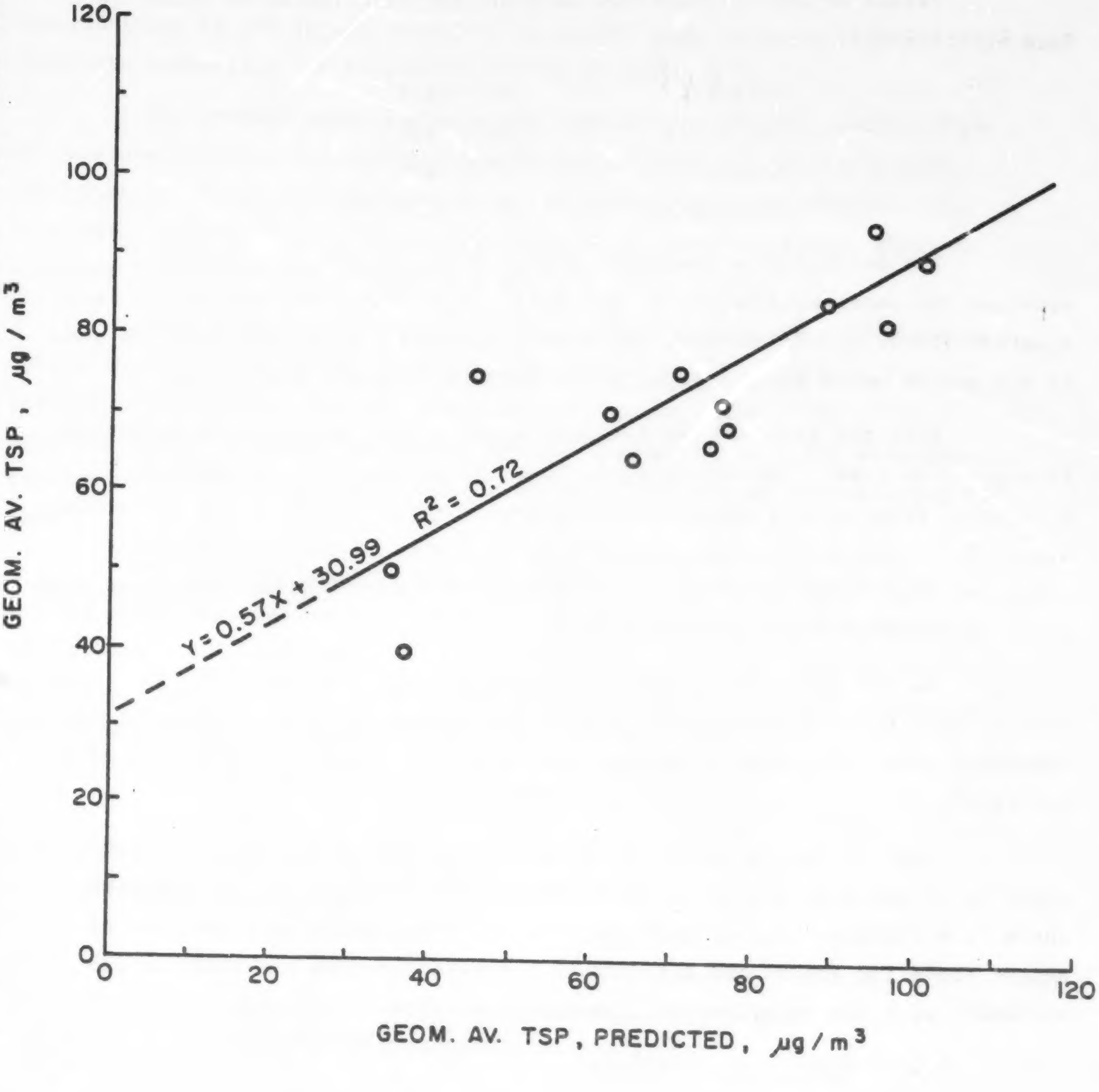


FIGURE 5·8 PLOT OF ANNUALLY ADJUSTED OBSERVED vs PREDICTED TSP USING PACE EQUATION.

Values of the city effects term for the four cities in which the Pace equation was developed are:

Portland	-	35.6 μg/m^3
St. Louis	-	50.6 μg/m^3
Kansas City	-	57.2 μg/m^3
Birmingham	-	50.3 μg/m^3

The point source component predicted by the Hamilton-specific equation was substantially lower (2-5 μg/m^3) than that predicted by the Pace equation (14-27 μg/m^3) and this difference possibly can be attributed to some of the points noted above regarding the Hamilton-specific derivation.

Both the Farm and SRC background sites show no predicted influence from point sources. The School site, however, is predicted to receive 5-27 μg/m^3 from point sources which represents about 10-50% of the TSP at this site. This results from the proximity of this site to the heavily industrialized area of Hamilton and the frequency of meteorological conditions under which the site is downwind of this area.

At the three background sites (the School, Farm and SRC), the local term is zero in both derivations, due to the absence of local traffic in the immediate area. The area terms here are relatively small, ranging from about 1-8 μg/m^3.

Most of the variation in the predicted TSP values for the urban sites is in the area and the local terms in both derivations. As expected, there is a decrease in the predicted area and local terms as a function of height above the ground and distance of the receptor from the road, in good agreement with the experimentally observed profiles.

5.2.2 Dispersion Modelling

An extensive review of dispersion modelling in urban areas has been presented in Section 2.5. The urban model selected for use in this study and its characteristics are given in Section 3.10. The results of the model calculations and the general features and statistics of the data are outlined in Section 4.8 and tabulated in Appendix J. Therefore, this section will focus only on the source apportionment data available from the model at the Experimental site (primarily at site E-3).

The dispersion modelling results provide a breakdown of the contributions to TSP levels according to source type as shown in Table 4-36. These are summarized for the entire period in Table 5-7.

The overall results show a 20% overestimate of TSP levels. Part of this overestimate results from the method of handling the background contribution, since the remote site values contain a local contribution. This local contribution is especially evident at the School site which is situated 250 m from a major highway.

Another contributing factor to the overestimate lies in the area source inventory, which includes a component due to home and commercial heating sources which does not apply for the period under study. The modified street sweeping techniques applied during the last two experimental periods could, of course, also have produced a lowering of the observed TSP levels.

The combined results indicate a 12% contribution from the line sources which were separately modelled. Of the area source contribution, approximately 60% is related to traffic sources (vehicular exhaust plus reentrained dust). These results then indicate the following breakdown of particulate loading at E3 by contributing source:

Industrial Sector (Point Sources)	6%
Traffic Related	40%
Other Fugitive Sources (Area)	19%
Background Influx	35%

TABLE 5-7

Calculated Source Contributions to TSP at Experimental Site Over Entire Period

	Expt. 1		Expt. 3	
	$\mu g/m^3$	%	$\mu g/m^3$	%
Point	8	8	8	6
Area	41	42	61	47
Line	4	4	15	12
Background	46	47	46	35
Total (Arithmetic Mean)	98		129	
(Approximate Geom. Mean)	(88)		(116)	
Observed (Geometric Mean)	76		95	

It should be noted that, of the total traffic-related component at the E3 site, only one third is attributable to the immediately adjacent roadway. This fraction is still lower for the E1 site.

The contribution of the industrial sector sources from direct stack and vent emissions is estimated at 6% of total particulate at E3. This proportion will, of course, differ according to location, increasing in the proximity of the sources.

5.2.3 Chemical Mass Balance

Chemical mass balance (CMB) calculations are a form of receptor modelling (see Section 2.6) for which the methodology used in this study is outlined in Section 3.11. The results are presented in Section 4.7. CMB calculations produce results on an event basis and, since a large number of elements are needed in order to carry out the calculations, only the data from XRF analysis of the dichotomous sampler filters were used. This produced 53 sets of filter CMB analyses (fine fraction and coarse fraction) which were obtained during the mechanical and vacuum sweeping periods. The data apply to the Experimental site, E-3, and the Control site, C-3 (see Section 3.3).

Of the ten source elemental matrices used in the fitting, five groups were identified as significant contributors to the receptors. These were:

1. Road Dust - a road dust elemental matrix obtained from a direct collection and chemical analysis of dust samples from Cannon Street.
2. Transportation Component - a chemical fingerprint associated with direct vehicular exhaust.
3. Limestone Component - a crustal limestone component.
4. Steel/Iron Component - a combination of contributions from a composite source, open hearth furnaces, blast furnaces and basic oxygen furnaces.

5. Secondary Sulphate - this component represents the excess sulphur above that expected from the other fitted source components, fitted as ammonium sulphate.

An analysis of the data comparing the control and experimental sites shows that, overall, there are no differences (in a statistical sense) between them for the coarse and fine mass fractions collected. Both sites were also found to be the same with respect to the relative impacts of the various source components (where sufficient data were available). Thus, data from both sites can be pooled in order to evaluate the contribution of each source component to the observed receptor mass and the effect of meteorological parameters.

Road Dust Component. The road dust component was well characterized by chemical analysis and size determination of samples taken from Cannon Street. This component represented one of the largest single contributors to the total mass collected at the receptor sites for an average of about 24% of suspended particle mass with sizes below 15 µm aerodynamic equivalent diameter. Almost all of the road dust component was found in the coarse fraction (2.5 to 15 µm diameter) in which it accounted for about 50% of the mass. Road dust accounted for an average of only 2% of the mass in the fine fraction (diameter < 2.5 µm).

Both the Experimental and Control sites were located on the north side of Cannon Street. However, the percent contribution of road dust to the receptor particle loadings was found to be essentially independent of wind direction. The implication is that, although road dust from Cannon Street itself may be a contributing factor, it is not dominant. Road dust of similar chemical and size characteristics from surrounding streets, laneways and parking lots all combine to account for the observed contribution of this source to the receptor mass loading.

There was not a significant difference in the relative road dust contribution to the receptor loadings between the mechanical and vacuum sweeping periods at either the experimental or the control sites. This is discussed further in Section 5.3.

Transportation Component. This component represents particulate matter contributed by direct vehicular exhaust. The overall combined contribution of this source to the fine and coarse fraction was about 8%. The contribution to the coarse fraction, 4%, was smaller than that to the fine fraction, 12%, as is expected for this type of source.

There was not a statistically significant difference between the mechanical and vacuum sweeping periods; however, there was a strong dependence on wind direction. During periods under which the receptors were downwind of Cannon Street, the relative contribution of the vehicular component to the observed particle concentrations was twice that observed during periods when the receptors were upwind of Cannon Street. This result suggests that, unlike the road dust component, the particle mass arriving at the receptors which originates from vehicular emissions is heavily influenced by emission from Cannon Street. A reasonable estimate is that about 50% of this component is due to Cannon Street sources when the receptors are downwind of the street.

Limestone. In the Hamilton area, there are significant deposits of dolomitic limestone and it is, therefore, not surprising that the CMB analysis identified the crustal limestone component as significant. The average contribution of this component to the receptor particle mass loading was about 5%. All of this was concentrated in the coarse fraction (2.5 μm to 15 μm) which is expected for particles arising from erosion and reentrainment processes.

The relative contribution of this component appeared to be independent of wind direction. This is consistent with a general area-wide crustal source of airborne particles.

Steel/Iron Component. The steel/iron component is represented by four source types which were combined subsequently to the CMB apportionment calculations. This source was found to contribute a relatively small but significant amount to the total loading. Roughly equal contributions were found for both the coarse and fine fractions for a total of about 4% over the period of the study.

The percentage contribution of this component to the particle mass collected was found to be strongly dependent on wind direction. Relative contributions were about five times higher when the receptors were downwind of the heavily industrialized sector as compared to conditions when they were upwind.

Secondary Sulphate. Secondary sulphate was found to be one of the largest source components with an average contribution of about 29% to the particle mass collected. Almost all of this was in the small size fraction (< 2.5 μm). Concentrations ranged from about 2 $\mu g/m^3$ up to 25 $\mu g/m^3$. The relative contribution of this component was not significantly dependent on local wind direction.

These findings are consistent with general area-wide sources and the sulphate found can be largely attributed to the long-range transport of sulphate compounds to the receptors from outside Hamilton.

Quality of the CMB Results. The quality of a CMB fit depends on the accuracy and completeness of the source elemental matrix as well as the receptor matrix. In order to obtain reliable results, all sources do not need to be used. However, those contributing significantly to the particle mass observed and to the various elements used in the fitting should be included.

A potential weakness in this study is the lack of a directly measured source element matrix for all of the major sources. Since such data were not available for all sources, source "fingerprints" were obtained from the airshed studies and published information. This inferred source element matrix is suitable for semi-quantitative results and care should be taken in using the absolute value of these data.

Despite these caveats, the CMB analysis is suitable for defining the approximate contribution of each source category to the observed particle mass collected. These data are particularly useful in conjunction with other information such as the dependence of source component contribution on wind direction, dispersion modelling (Section 5.2.4) and microinventory calculations (Section 5.2.3).

The quality of the CMB fit is measured by three factors:

(1) the reduced chi square,

(2) the ratio of the calculated to measured values for each major chemical species,

(3) the percent of the total measured ambient concentration which is explained.

The coarse fraction showed a very good CMB fit due primarily to the fact that the road dust component was chemically well characterized by direct measurements and this component was a large fraction (50%) of the total mass in this size fraction.

The CMB source apportionment for the fine fraction was comparable in quality to that for the coarse fraction. The predominance of secondary sulphate and transportation sources in this fraction, buth of which are well characterized, and the inclusion of a comprehensive iron and steel component containing some Hamilton source data, are likely the reasons for the very good fit.

Summary. The CMB results are summarized for the study average percent contribution in Table 5-8.

In the coarse fraction, the road dust is the largest component at about 50%. The next most significant source is that due to the iron/steel component of about 8%, while the transportation and limestone/construction components are smaller at 5% each. The secondary sulphate component is very small at only 3%. The fine fraction's largest component is secondary sulphate at 56% followed by transportation, 13%, and steel/iron, 8%. There is also a small road dust component of 2% in the fine fraction.

Over 90% of the road dust component is found in the coarse fraction. This is consistent with the distribution found in the collected road dust samples at the experimental and control sites. About 80% of the transportation component was found in the fine fraction. This is consistent with the results of other studies of this component in urban areas (64,206). The crustal limestone component arises primarily from erosion and reentrainment and, as expected, is all found in the coarse size fraction. The sulphate component is attributable to long-range transport for which, as observed, almost all of this chemical species is expected to be in the fine size fraction.

The steel/iron component was approximated by the use of four source fingerprints:

TABLE 5-8

Chemical Mass Balance Results

Composite Sources	Average Percent of Mass Coarse Fraction (2.5 - 15 microns)	Fine Fraction (<2.5 microns)
Road Dust	50	2
Transportation	5	13
Limestone/construction	5	0
Secondary sulphate	3	56
Steel/iron Sources	8	8

(1) an integrated iron/steel complex composite profile

(2) a Hamilton blast furnace profile

(3) a Hamilton basic oxygen furnace profile

(4) a Portland blast furnace profile

These individual source fingerprints may be indicative of the specific source which is implied by the name, but they do not necessarily represent an accurate reflection of the emission matrices for the steel works in Hamilton. However, they are suitable as a reasonable fit for the enrichment in certain metals (e.g., Fe, Mn, Cu, Zn) found at the receptors and attributable to the steel works.

The road dust, limestone and secondary sulphate components did not show a significant local wind direction dependence. This is expected for area-wide sources such as crustal limestone and for secondary pollutants such as sulphate. However, the results were somewhat surprising for road dust. This indicates that this component is not dominated by the nearby Cannon Street source and that other streets in the area, laneways and parking lots are all significant sources of road dust which is transported to the receptor sites.

The CMB data represent source apportionments for the time periods during which the samples were collected at the receptor sites. Averages and other statistics apply only under similar sets of source emission characteristics and prevailing meteorological conditions. Accurate extrapolation to other time periods requires characterization of the source apportionment by principal sets of conditions and application of the data to the frequency of occurrence of these conditions over the time period of interest.

Influence of Meteorological Regimes on CMB Results. Statistical tests were carried out to determine whether significant differences existed between the percent contributions of various components averaged over the two meteorological regimes: wind direction from the SSW sector (r_1) and wind direction from the NE sector (r_2). The following components were tested:

- road dust (coarse fraction)
- transportation (inhalable fraction)
- limestone/construction (coarse fraction)
- iron/steel composite (inhalable fraction)
- secondary sulphate (fine fraction).

The only one of these that showed a statistically significant difference for these two regimes was the iron/steel composite. The mean value of the percent contribution to the indicated particulate fraction for the iron/steel composite was significantly greater when the wind blew from the r_2 (industrial) sector than when it blew from the r_1 (street and city) sector. The difference was significant at the 95% confidence level, but not at the 99% level.

During individual sampling periods, the following range of values of the percent contribution in the < 15 μ fraction was observed for the iron/steel component:

	Regime							
	r_1				r_2			
Component	**Min.**	**Mean**	**Max.**	**n**	**Min.**	**Mean**	**Max.**	**n**
COMP (Exptl)	1%	1.8%	4.6%	17	1.7%	7.9%	14%	11
COMP (Control)	0.3%	2.3%	6.0%	16	8%	12%	22%	7

Thus, under certain meteorological conditions, the relative contribution of the industrial sources was three times their overall average contribution, and the regime averages were in a ratio of 5:1 (r_2:r_1).

5.2.4 Comparative Summary

As discussed at the beginning of this section, source apportionment of urban particles must rely on the combined evidence provided by several methods, each of which has some technical weaknesses. However, taken together, these different approaches present a consistent picture from which reliable conclusions can be drawn.

The semi-quantitative methods on which this study primarily depends were the microinventory, chemical mass balance calculations and dispersion modelling. The results of these methods are individually discussed in the previous sections.

The source categories used were slightly different for each method and, therefore, in order to produce a comparative summary, the data need to be organized under common sources. These are summarized as follows:

(1) Area sources: this includes combustion sources such as fuel for heating, incinerators, and fugitive dust sources such as construction and demolition activities, reentrained dust, agricultural activities, etc. Minor point sources are also included here.

(2) Point sources: these include the major industrial point and fugitive emission sources. This is primarily the steel industry component.

(3) Traffic-related: this includes both direct vehicular emissions and reentrained road dust.

(4) Background: this source is primarily the baseline particulate matter concentration contained in air masses as these are advected into Hamilton. This represents the approximate levels of TSP to be expected if there were no additional urban sources.

Dispersion Model. The results of the dispersion modelling calculations are already in the right form to match the source components as listed above (Section 5.2.2) and, therefore, no further data manipulations are required.

Chemical Mass Balance. Area sources were determined by combining the limestone, construction, incineration, and residual oil source components. The point source was the steel/iron components and the traffic related source was represented by the sum of the road dust plus the transportation component. Background is the sulphate component expressed as ammonium sulphate.

Microinventory. The microinventory data used are those based on the results of both Pace's equation and the Hamilton-specific deviation (see Section 5.2.1) for the Experimental site (E-3). The area term was adjusted by removal of that portion which was traffic related. This reduced the area term by about 57%. The local term was added to the traffic related portion of the area terms to give a total traffic related term.

The results of the three apportionment methods are summarized in Table 5-9. The agreement of the percent contributions for the source categories between each method is remarkably good. In view of the expected variations in these data, this precision must be regarded as somewhat fortuitous. However, the approximate relative contribution of each source category is considered to be reliable.

The 'unexplained' portion of the mass by the CMB method would be distributed among all four source categories. This portion of particulate matter loading is very likely dominated by carbon (elemental and organic), nitrogen compounds (including nitrates), oxygen and hydrogen (predominantly in the form of water of hydration in crystalline material).

The measurements of carbon on HiVol filters, documented in Tables 5-4, 5-5 and 5-10, imply a mean carbon loading of about 13% of TSP (about 4.5% elemental and 8.5% total organic mass). This contribution would be divided between the 'point' and 'traffic-related' categories in the form of combustion and coking emissions for the former and tailpipe emissions for the latter, and might contribute to 'area' in the form of combustion emissions. No estimate of the relative partitioning can be given on the basis of current information.

Nitrates and water of hydration would contribute significantly to the secondary of 'background' category. If these make up the remaining, non-carbon portion of the unexplained mass (12%), then the 'background' category would increase to 42%.

The largest contribution of particulate matter to the receptor (Experimental site, E-3) over the study period was that due to traffic related sources. The average contribution of this source was about 40% of which, based on the ratio of road dust and transportation components from the CMB data in Section 5.2.3, road dust reentrainment would account for 30% and vehicular exhaust 10%. For particulate matter below about 15 μm in diameter (as represented by the dichotomous sampler data used in the CMB calculations) the road dust component thus represents about 14 $\mu g/m^3$ (25% of 55 $\mu g/m^3$). The total loading of the road dust component in TSP would be greater than the 14 $\mu g/m^3$ loading in the inhalable portion. It is this loading which could potentially be reduced by street cleaning methods.

TABLE 5-9

Comparative Summary of Source Apportionment Results

Source Category	Percent Contribution Microinventory[a]	CMB	Dispersion Model
Point	2-17	8	6
Area	16-2	3	19
Traffic-Related	48-27	34	40
Background	34-54	30	35
Unexplained	-	25	-

[a] The range of values reflects the results of the two derivations (Pace, Hamilton-specific) described in Section 5.2.1.

TABLE 5-10

Organic and Elemental Carbon Content of Total Suspended Particulate Mass

SITE	DATE[1] (Dichotomous Run Start)	INHALABLE[2] MASS CONCENTRATION $\mu g/m^3$	TSP ($\mu g/m^3$)	HI-VOL[1]		Estimated Total[3] Organic Mass ($\mu g/m^3$)
				Org C ($\mu g/m^3$)	Elem C ($\mu g/m^3$)	
Expt.	7/10	68.8	125	7.1	7.1	9.9
Expt.	8/1	42.0	92	8.6	5.5	12.0
Expt.	8/3	60.7	142	11.9	9.4	16.7
Expt.	8/6	43.2	100	5.5	5.5	7.7
Expt.	8/7	93.2	318	18.3	12.5	25.6
Control	7/10	51.9	125	9.6	4.6	13.4
Control	7/27	51.8	142	11.4	6.2	16.0
Control	8/1	85.1	108	4.2	7.1	5.9
Control	8/3	68.8	142	9.4	8.2	13.2
Control	8/6	42.5	100	6.0	4.8	8.4
Control	8/7	75.7	318	12.8	5.9	17.9
Mean		62.2	156	9.5	7.0	13.3

1. There is a 6 hour overlap of hi-vol (6 hour) runs and dichotomous runs (12 hour) except for dichotomous sample started 8/1 at 1800 at the Control Site for which two hi-vol filters overlapped the dichotomous sampling period. The hi-vol data presented in tables for 8/1 at the Control Site is the average of the two filters

2. Sum of fine and coarse dichotomous filter pairs.

3. Organic carbon content multiplied by 1.4.

The background figures for the microinventory and the dispersion model calculations are not fully independent calculations and, in fact, arise as a residual term dominated by the results from the three background sites. The average value of ∿ 40% is large but not suprising (see Section 3.4).

The area sources averaged about 10% of the aerosol mass. This source is somewhat larger than the point source average contribution of about 7%. Thus, despite their visually obvious presence, point sources contribute a relatively small fraction to the total observed receptor aerosol mass at the experimental site as measured over the study period.

A possible rationalization for the relatively low 'area' contribution determined for the CMB approach (in agreement with the Hamilton-specific inventory) is that the emissions from local unpaved parking lots, aggregate piles, etc., were so similar to the road dust samples that most of the 'area' sources became embedded in the 'road dust' component of the CMB and, thus, appeared to be traffic-related. This explanation would also account for the unexpected lack of wind directionality of the 'road dust' contribution. Some of the 'unexplained' mass may also have been attributable to the 'area' category. Carbon from nearby combustion sources would have been overlooked by the CMB, since this element was not a parameter in the analysis for the filters used in the CMB.

5.3 Evaluation of Street Sweeping Methodologies

5.3.1 Study Objective and Design

As described above, three distinctly different approaches have been used to determine the relative contribution of various source categories to ambient TSP levels in the study area. The excellent agreement in the results obtained (Table 5-9) allows considerable confidence in the conclusion that traffic-related source categories account for ∿ 40% of airborne particulate matter in the Hamilton urban area. This conclusion is consistent with the findings of earlier studies (Sections 2.3, 2.4, 2.6) and indicates that measures to minimize the reentrainment of street dust should be part of any urban particulate control strategy.

Street cleaning on a regular schedule is a main component of the street maintenance programs conducted by most cities and towns. The ability of the various types of sweepers to remove accumulated dust and debris from the street surface is well documented and the aesthetic value and desirability of such programs is apparent. However, the effectiveness of street sweeping as a control measure for the reduction of ambient TSP levels in an urban area is not well defined, with conflicting conclusions resulting from earlier studies (Section 2.7).

In this study, both mechanical and vacuum sweepers of conventional design were evaluated, with special emphasis given to the establishment of "baseline" or reference conditions against which to measure the effect of street-cleaning activities on TSP levels. The first phase of the study (up to July 7, 1979) was used to gather baseline data in conjunction with normal street-cleaning activities and to establish the relationship between TSP levels at the Experimental and Control sites under typical summertime conditions. As described earlier (Section 3.5), mechanical sweeping was then implemented in the vicinity of the Experimental site during the second phase of the study, with the area being swept once during each night and morning shift (see Figure 3-23). During the third phase of the experiment, vacuum sweeping was applied in the same way. Although the operators of the sweeping equipment generally followed a predetermined route through the streets during each shift, it was not feasible, nor relevant, to attempt to show the effect of specific, individual street sweeping events on the TSP loadings measured adjacent to the roadway. Instead, the objective of the study was to determine if the increased frequency of street-sweeping reduced to a significant extent average TSP loadings in the study area.

The experimental design of the study can be summarized as follows:

	Sweeping Activity at	
Study Phase	Experimental Site	Control Site
1	Normal	Normal
2	Mechanical (twice daily)	Normal
3	Vacuum (twice daily)	Normal

In the initial conceptual design of the study, the immediately adjacent roadway (Cannon Street) was perceived to be the predominant source of reentrained particulate matter at both the Experimental and Control sites and so considerable emphasis was given to the determination of height and distance profiles. The anticipated decrease in loadings as a function of height and distance is observed and this feature of the data has been discussed above (see Section 5.1). However, both the microinventory and dispersion modelling show that immediately adjacent roadways make a smaller per cent contribution than anticipated. The microinventory studies, for example, indicate approximately equal contributions by the "Area" and "Local" (Cannon Street) terms. The dispersion modelling results are consistent with this apportionment and further show that the immediately adjacent line sources probably contribute not more than 12% of the TSP loadings, and approximately 60% of the "Area" term emissions are traffic-related.

5.3.2 Statistical Evaluation of TSP Data

The street sweeping experiment involved the entire area (see Figure 3-23) surrounding the Experimental site and, therefore, could be expected to have an effect on both the "Area" and the "Line" contributions to TSP loadings. Because of this, primary attention has been given to the data for the E3 and C3 monitoring sites in assessing the effects of street sweeping. The significance of the observed height and distance profiles and the otherwise similar characteristics of the measurements as a function of height and distance have already been discussed (Section 5.1). Furthermore, the largest effect of street sweeping can be expected to occur at E3.

TABLE 5-11

Summary of Observed TSP Loadings (geometric mean, $\mu g/m^3$) for the Three Sweeping Periods

	Experimental		Control	
	E1	E3	C1	C3
Baseline	76	90	76	92
Mechanical Sweeping	85	108	89	108
Vacuum Sweeping	74	89	79	98

Inspection of Table 5-11 reveals several apparent features of the average TSP levels for the three periods:

- TSP loadings at the upper levels (E1, C1) are consistently lower than at the lower levels (E3, C3) but show similar trends from site to site and period to period.
- Very similar values occurred at the Experimental and Control sites, at both levels, during the Baseline period.
- Average TSP loadings were higher during the Mechanical sweeping period than during the Baseline period, but very similar loadings occurred at both sites, suggesting that some factor other than sweeping caused these higher loadings.
- The average TSP loading at E3 during the vacuum sweeping period was very similar to that for the Baseline period, but somewhat lower than the value at the Control site, suggesting a small reduction resulting from vacuum sweeping.

These and other features of the TSP data for the three periods can be used to reach the following tentative conclusions:

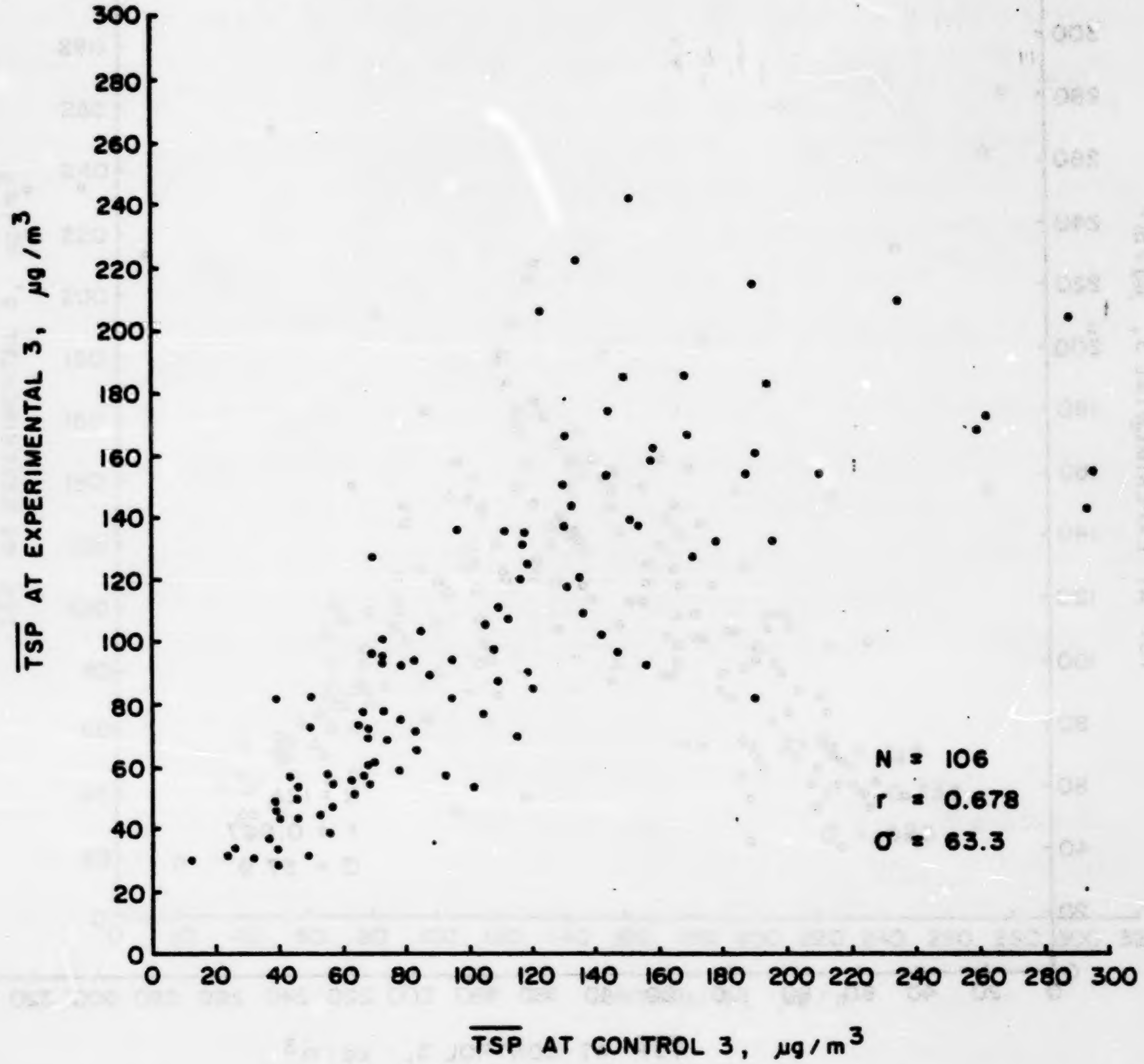
- Source characteristics, and hence the average TSP loadings, are quite similar at both sites. In addition to the similar loadings which occurred during the Baseline period, note the very similar and consistent diurnal profiles (Figures 4-2 to 4-5) determined for the various sites and periods. Directional distributions of average particulate loadings and dosages also are quite similar for the two sites (Figures 5-3 and 5-4).
- It is unlikely that the higher loadings observed during the second period are due to the increased frequency of mechanical sweeping. Prevailing meteorological conditions did change from period to period. Different wind frequency distributions occurred (Figures 4-9 and 4-10) during the three periods and the occurrence of conditions conducive to higher TSP loadings has been confirmed by the dispersion modelling results (Section 4.8).
- Increased frequency of vacuum sweeping may have resulted in a small reduction in TSP loadings at the Experimental site.

A relatively high degree of variability is a normal feature of ambient pollutant measurements in an urban area. The degree of variability in the relationship between concurrently measured 6-hour TSP levels is shown in Figures 5-9 to 5-11, and a linear regressional equation for the data is given in each case.

Only a relatively small number (∿ 6) of outliers have been rejected from the data sets. This was done on the basis of comparison with the values at the other sites (E1, E2, C1, C2, etc.) and, in each instance of rejection, either E3 or C3 was obviously inconsistent with these values. There is an obvious correlation between the individual pairs of measurements with correlation coefficients in the 0.68 to 0.87 range. For data sets of this magnitude, r values in this range indicate a strong linear relationship between the two sites.

The mean standard deviation is ∿ 60 $\mu g/m^3$, compared with average values in the 75-110 $\mu g/m^3$ range. Thus, it is apparent that statistically rigorous methods must be used if quantitative conclusions regarding the significance of the relatively small differences in TSP levels for the 3 periods are to be drawn. Since the data show a log normal distribution, the standard paired t-test was used to determine whether or not there is a statistically significant difference between TSP levels at the Experimental and Control sites. All sampling periods without precipitation were used, since the possibility of significant rainout of particles during precipitation make these sampling periods less favourable for assessing street sweeping effects.

The results of the paired t-test are shown in Table 5-12 and indicate that the average TSP levels during both the Baseline and Mechanical periods were not statistically different at the 95% confidence interval. For the Vacuum Sweeping period, the test indicates that the slightly lower levels measured at the Experimental Site (Table 5-11) are statistically different than concurrently measured levels at the Control Site. However, it should be noted that the calculated t-value is only marginally larger than the theoretical t-value for this level of significance, consistent with the relatively small difference (∿ 7%) in the geometric mean values.



EQUATION OF BEST LINE y = 0.65X + 37

FIGURE 5-9 COMPARISON OF EXPERIMENTAL 3 AND CONTROL 3 BASELINE PERIOD.

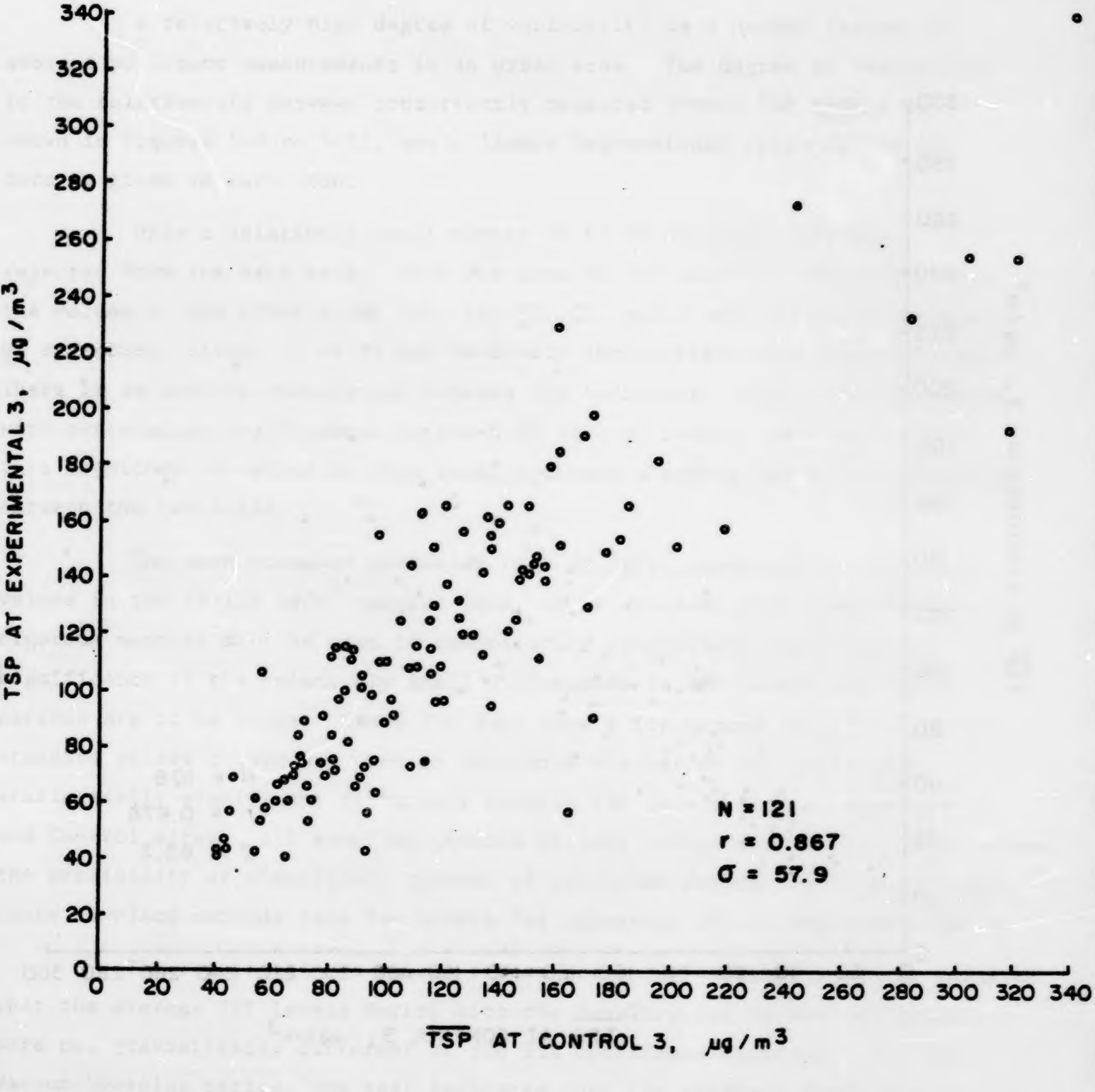
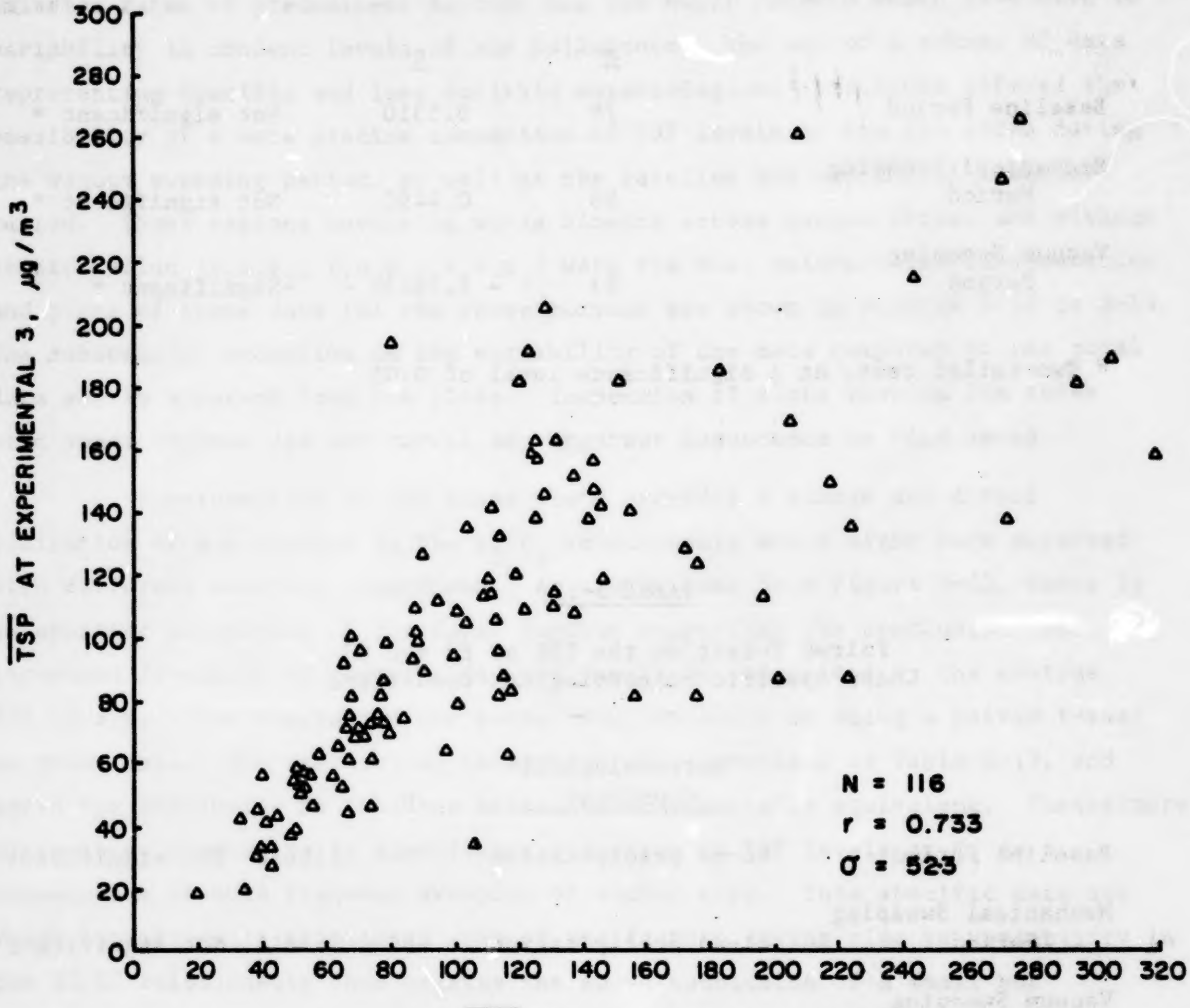


FIGURE 5·10 COMPARISON OF EXPERIMENTAL 3 AND CONTROL 3 MECHANICAL SWEEPING PERIOD.



EQUATION OF BEST LINE $y = 0.61X + 35$

FIGURE 5·11 COMPARISON OF EXPERIMENTAL 3 AND CONTROL 3 VACUUM SWEEPING PERIOD.

TABLE 5-12

Paired T-test on the TSP at E3 and C3 for all Sampling Periods Without Precipitation

	n	t	
Baseline Period	78	0.5310	Not significant *
Mechanical Sweeping Period	96	0.4490	Not significant *
Vacuum Sweeping Period	83	- 3.7945	Significant *

* Two-tailed test, at a significance level of 0.05

TABLE 5-13

Paired T-test on the TSP at E3 and C3 Under Specific Meteorological Conditions

	Meteorological Condition	n	t	
Baseline Period	R1-no precipitation	54	1.8610	Not significant *
Mechanical Sweeping Period	R1-no precipitation	59	0.3614	Not significant *
Vacuum Sweeping Period	R1-no precipitation	42	1.8860	Not significant *

* Two-tailed test, at a significance level of 0.05

Changing meteorological conditions and short-term variations in the emission rates of predominant sources are the major factors which give rise to variability in ambient levels of air pollutants. The use of a subset of data representing specific and less variable meteorological conditions offered the possibility of a more precise comparison of TSP levels at the two sites during the vacuum sweeping period, as well as the baseline and mechanical sweeping period. Those regimes involving winds blowing across Cannon Street and without precipitation ($r_1u_1p_2$, $r_1u_2p_2$, $r_1u_3p_2$) were the most relevant for consideration and plots of these data for the three periods are shown in Figures 5-12 to 5-14. The substantial reduction in the variability of the data compared to the total data set is apparent from the plots. Inspection of plots showing the three wind speed regimes did not reveal any apparent dependence on wind speed.

Superposition of the three plots provides a simple and direct indication of any changes in the E_3/C_3 relationship which might have occurred with different sweeping conditions. As can be seen from Figure 5-15, there is no apparent separation of the data, further supporting the conclusion that increased frequency of sweeping did not result in reductions in the average TSP levels. This conclusion was tested statistically by doing a paired t-test on these data. The statistical parameters are summarized in Table 5-13, and again the conclusion is that the sites are statistically equivalent. Furthermore, there is no statistically significant reduction in TSP levels at E_3 as a consequence of more frequent sweeping of either type. This specific data set which intentionally eliminates some of the factors giving rise to variability in the E3/C3 relationship thus negates the above conclusion of a small but marginally significant reduction by vacuum sweeping.

It is apparent from the above statistical tests that any small reductions in TSP levels during the sweeping periods may be obscured by the variability in the data arising from other factors such as traffic, wind direction and wind speed.

Using the E3 and C3 TSP data for the r_1 (N to E winds) and r_2 (SSE to WNW winds) regimes, stepwise multiple regressions were performed to statistically express the difference in TSP concentrations at E3 and C3 as a function of TSP levels at C3, traffic counts and wind speed. Wind direction was allowed for by treating the r_1 and r_2 regimes separately. Thus, the

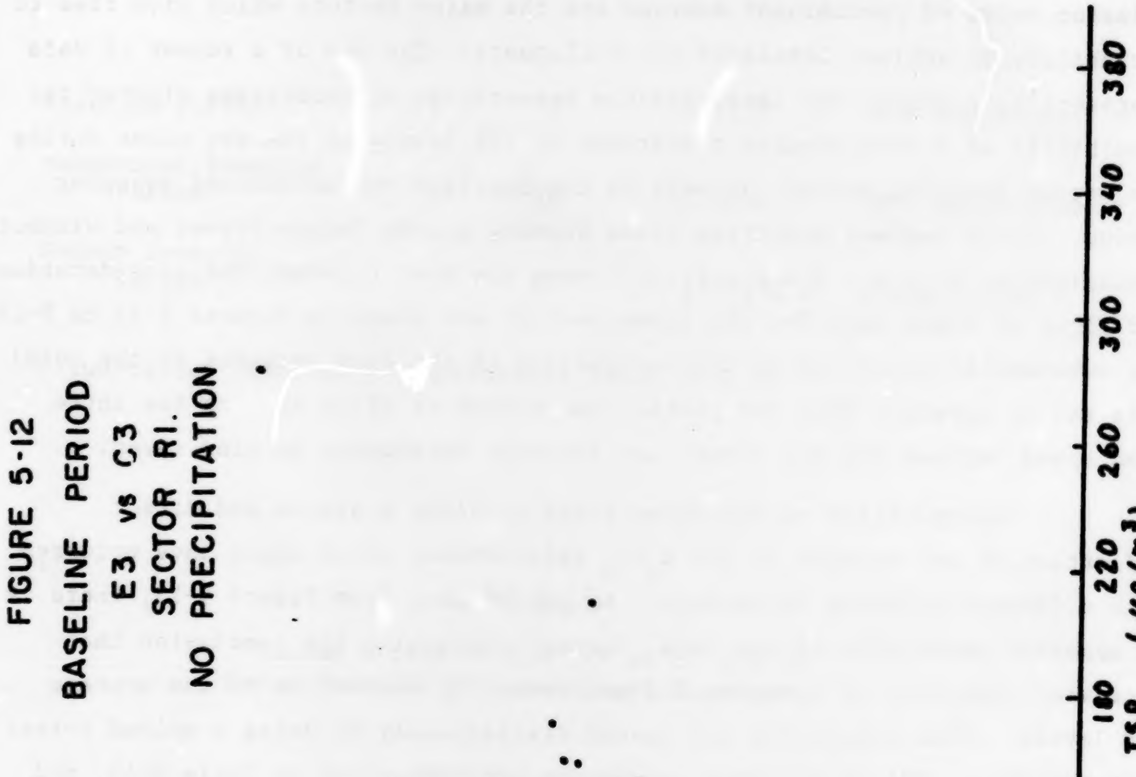


FIGURE 5-12
BASELINE PERIOD
E3 vs C3
SECTOR RI.
NO PRECIPITATION

FIGURE 5-13

MECHANICAL SWEEPING PERIOD
E3 vs C3
SECTOR R1
NO PRECIPITATION

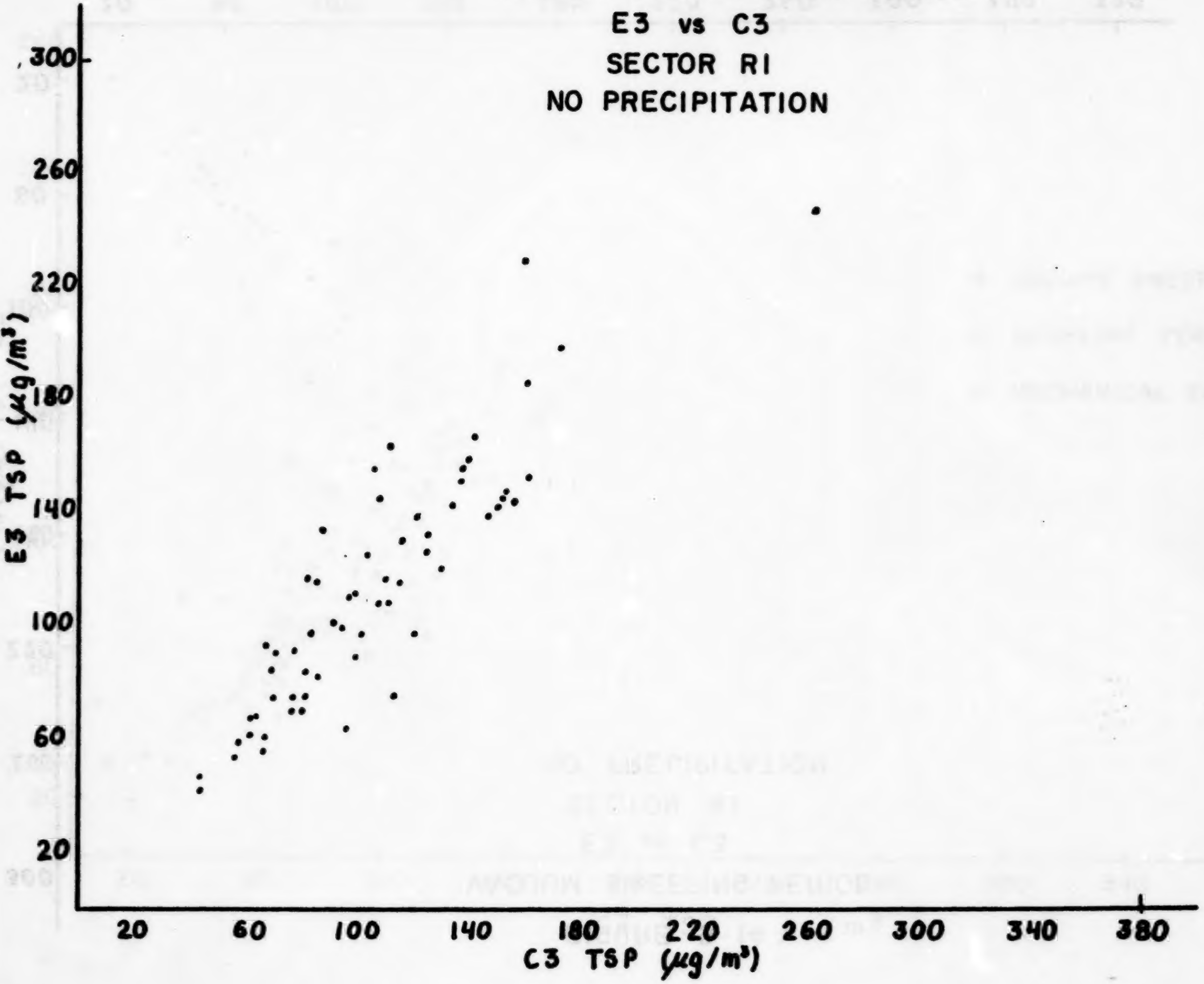
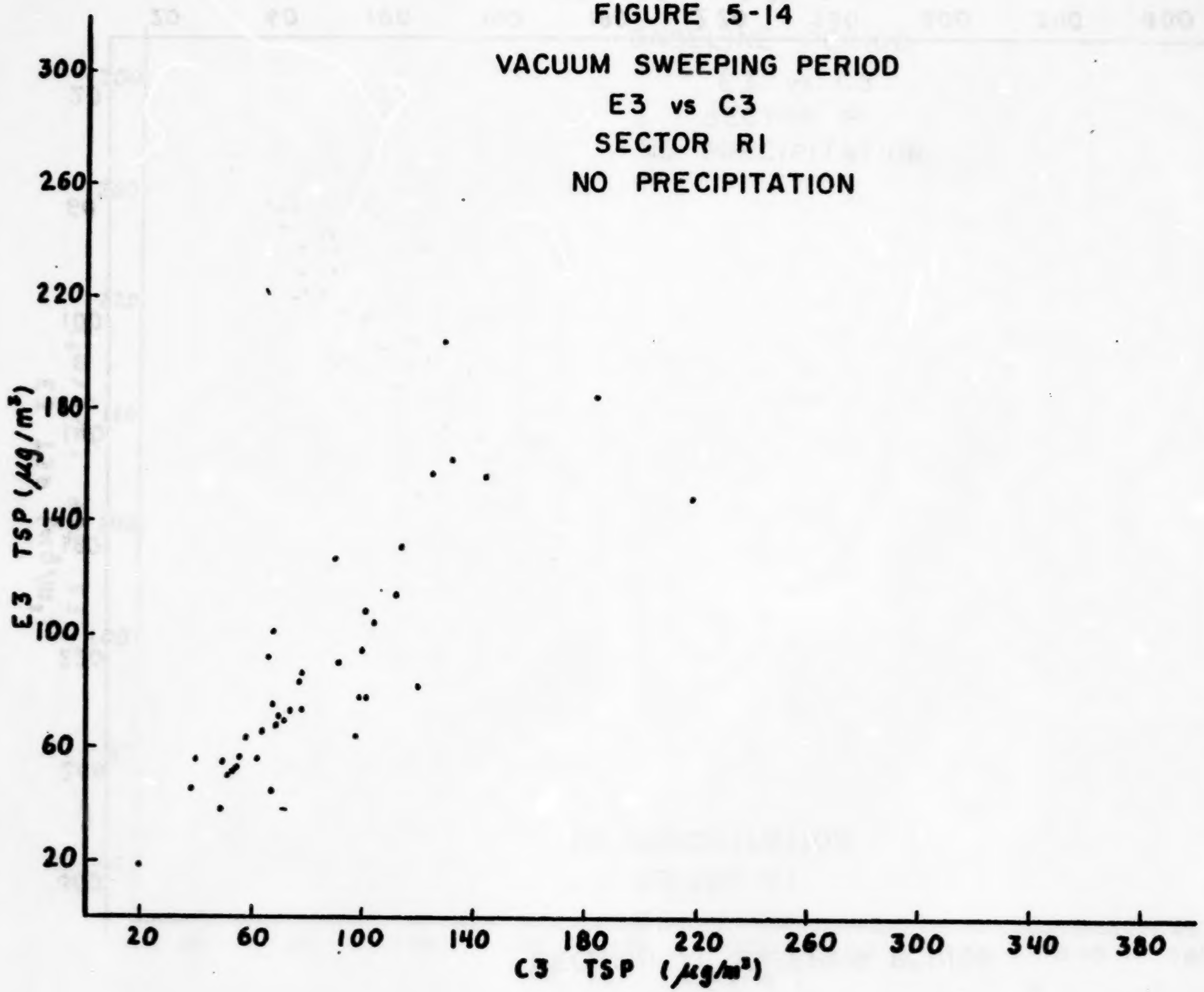


FIGURE 5-14

VACUUM SWEEPING PERIOD
E3 vs C3
SECTOR RI
NO PRECIPITATION



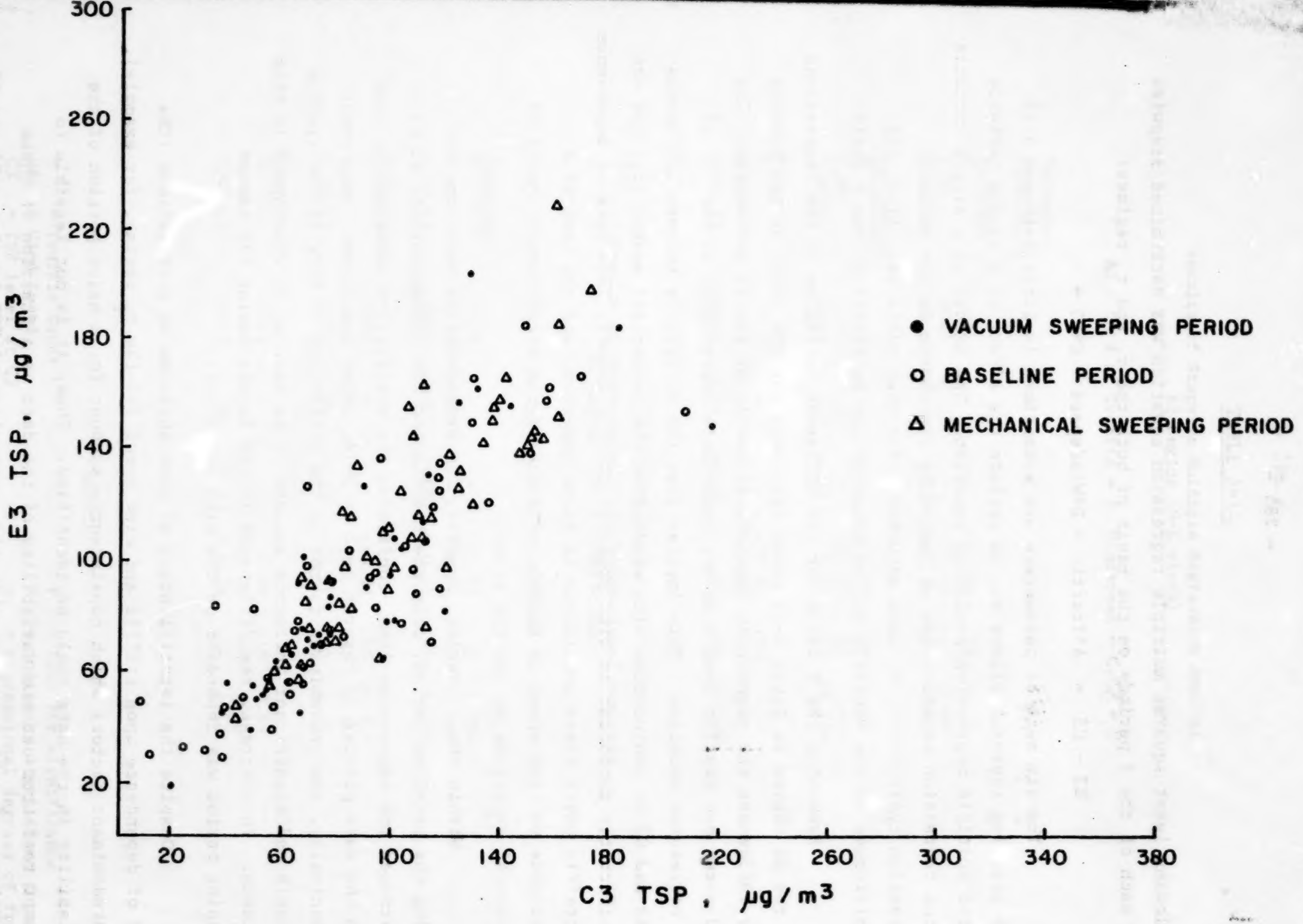


FIGURE 5-15 COMPARISON OF E3 & C3 TSP; ALL RI; NO PRECIPITATION.

following least squares multiple regression equation was determined stepwise for each of the 3 periods on the basis of both the r_1 and r_2 regimes:

$$E3 - C3 = A*Traffic + B*Windspeed + C*C3 + 0$$

The six sets of parameters are summarized in Table 5-14 and 5-15. This stepwise approach allows one to explore the effect of a single variable on the multiple regression predicted equation. The impact of a single variable on the regression equation can be judged by the change in the multiple regression coefficient, r, upon adjustment for that variable. Also, the significance of the variable to the equation can be tested by the F ratio.

Examining the F ratio for the different variables in the regressions for the R2 regime in Table 5-14 shows that only the TSP level at the Control site influences the regression line significantly at the 95 percentile. The wind speed and traffic counts do not contribute appreciably to the fit of the regression equation. This implies that the difference between TSP levels at E3 and C3 in conjunction with winds from the industrial sector (r_2) are not significantly dependent on wind speed or traffic counts. This lack of dependence on traffic under these conditions is quite expected, and the lack of a dependence on wind speed is further evidence of the proportional impact of industrial emissions on the two sites.

Within the r_1 sector, however, the dependence is more complex. During the baseline period, only the traffic and TSP concentrations at C3 determined the regression line, confirming the qualitative observations made from the data plotted in Figures 5-12 to 5-14. When the streets were swept mechanically, the predominant factor in the difference of TSPs is the traffic variable and significant influence appears to be exerted by wind speed in this instance. In contrast, the difference in TSP levels during the vacuum sweeping period was dependent on the wind speed only.

Despite the identification of some anticipated correlations (the lack of dependence upon traffic and wind speed for the r_2 regime, for example), no predominant factors which consistently account for a major portion of the variability in the data could be identified. Thus, it is not feasible to attempt to factor out the variability of the data as a function of these parameters and make a more quantitative comparison of TSP levels at E3 and C3

TABLE 5-14

Results of Stepwise Multiple Regression Analysis R2 Regime (N-E winds)

E3 - C3 = A. Traffic + B. Windspeed + C.C3 + C

Parameter Considered	A	B	C	D	r	f	n_1	n_2
Baseline							3	16
T	.0024	-	-	-41.48	.10	0.19		
T,WS	.0068	-3.19	-	-37.46	.19	0.44		
T,WS,C3	.0096	-3.36	-.39	+13.38	.60	7.93*		
Mechanical							3	28
T	.0013	-	-	-27.62	.07	0.17		
T,WS	-.0007	1.52	-	-33.00	.18	0.83		
T,WS,C3	.0042	- .07	-.29	5.32	.65	19.19*		
Vacuum							3	27
T	-.0013	-	-	-33.54	.06	0.12		
T,WS	-.0013	1.44	-	-47.01	.14	0.41		
T,WS,C3	-.0011	2.03	-.39	.81	.58	13.27*		

TABLE 5-15

Results of Stepwise Multiple Regressional Analysis R1 Regime (SSE to NNW Winds)

E3 - C3 = A. Traffic + B. Wind Speed + C.C3 + D

Baseline							3	50
T	.0073	-	-	-11.58	.32	6.09*		
T,WS	.0069	.370	-	16.07	.33	.08		
T,WS,C3	.0092	1.007	-.037	- 0.64	.46	6.76*		
Mechanical							3	55
T	.0066	-	-	-10.83	.55	24.31*		
T,WS	.0028	1.78	-	-17.34	.62	8.34*		
T,WS,C3	.0020	1.89	0.82	-24.67	.63	1.12		
Vacuum							3	31
T	.0014	-	-	2.06	.15	0.83		
T,WS	.0005	1.34	-	-13.05	.40	5.33*		
T,WS,C3	.0012	1.35	-0.13	- 4.58	.44	1.13		

LEGEND

T = Traffic Count
WS = Wind Speed
C3 = TSP level at C3
r = correlation coefficient

F = test for significance
* = indicates significant f ratio
n_1 = regressional degrees of freedom
n_2 = residual degrees of freedom

during the three periods. Thus, the statistical approaches used lead to the conclusion that increased frequency of either type of sweeping does not significantly reduce average TSP levels.

5.3.3 Dispersion Modelling Results

The dispersion modelling results have been used primarily to illustrate the dependence of TSP levels on meteorological factors such as wind direction and speed (Section 4.8), and to assess the relative contribution of various source categories (Section 5.2.2). However, the model has also been used to assess the conditions associated with the three sweeping periods, and the model predictions of TSP levels at E3 for the three periods compares with actual levels as follows:

Period	E3 Calc.	E3 Actual	C3 Actual
1. Baseline	111	108	112
2. Mechanical	152	119	120
3. Vacuum	123	100	113
% change 2/1	+ 37	+ 10	+ 7
3/1	+ 11	- 7	+ 1

Both the E3 and C3 sites show a marked increase in TSP for the Mechanical period. The model predictions indicate an even more pronounced increase for the second period, showing that meteorological conditions were at least partly responsible for the large increase observed during this period.

For the Vacuum Sweeping period, a smaller increase in TSP levels is predicted over the Baseline period and only a very slight increase is observed at C3. However, E3 shows a decrease of 7% in TSP for this period. Thus, the model results are qualitatively consistent with the possible conclusion that the suppression of TSP during the Vacuum Sweeping period is related to a real reduction in source strength, rather than to a modified dispersion regime. This interpretation of the experimental data in conjunction with the modelling results would be consistent with the earlier observation (Table 5-11) that a difference of marginal statistical significance did exist between TSP levels at E3 and C3 during the Vacuum Sweeping period.

If it is assumed that the 7% decrease in TSP at the Experimental site is a result of decreased road dust from the local line source, and approximately half of the area source (see Section 5.2.2), then the 7% decrease results from the control of approximately 25% of the sources responsible for the TSP loadings at the Experimental site. This implies a reduction of approximately 30% in road dust emissions as a result of the vacuum sweeping operation during the third period. This analysis suggests that substantial efficiency for roadway dust removal by street sweeping would be required to produce an observable effect on ambient TSP levels in most urban areas.

5.3.4 CMB Results

The results of the CMB calculations also can be used as a potentially sensitive test to determine if the mechanical or vacuum sweeping control methods had any significant effect in the reduction of particle concentrations at the receptor sites. The road dust source component was well characterized during the study period and CMB source apportionment calculations were the most reliable for this source. Any effect of street sweeping should be noticeable by comparing the road dust component between the Experimental and Control sites.

A subset of data from the dichotomous filters was selected for which there were matching pairs of valid samples at the Experimental and Control sites. A total of fifteen sets were available during the mechanical sweeping period and four sets during the vacuum sweeping period. No paired data were available during the background period. There was a substantial variability in the data and, in order to specifically investigate the effects of street sweeping, matched pairs of CMB calculations were compared for differences between the Experimental and Control sites using the paired t-test. This statistical analysis of the relative contributions from the major source components identified in the CMB calculations showed that, overall, the Experimental and Control sites were not significantly different from each other.

This statistical analysis was carried out on the relative contributions of each component in order to reduce the influence of one source of variance - the fluctuation in total particle loadings at the two sites - that makes a large contribution to the standard deviation of the mean difference of the total particle loading between the sites.

The paired difference between percent contributions of the road dust component to the loading at each site is a more stable and sensitive parameter than the corresponding difference between the total loadings themselves.

During the mechanical sweeping period (15 filter pairs), the mean contribution of the road dust component in the coarse fraction (where almost all of the road dust is found) at the Experimental site was 56% and at the Control site 46%. This difference of 10% (Experimental > Control) is statistically significant at the 95% confidence level, but not at the 99% level.

During the vacuum sweeping period (4 filter pairs), the analogous relative contribution of the road dust component (coarse) at the Experimental site was 37% and at the Control site, 47%. This difference of about 10% (Experimental < Control) is also significant at the 95% confidence level but not at the 99% level.

The differences in relative contribution of road dust identified as statistically significant above should be placed in context. Since the mean coarse fraction loadings during the mechanical sweeping period were 26 and 32 $\mu g/m^3$ at the Experimental and Control sites, respectively, and 12 and 13 $\mu g/m^3$, respectively, during the vacuum sweeping period, the 10% increase or decrease indicated above would amount to only about one to three $\mu g/m^3$ in either case.

The conclusion is that there was no substantial effect on the aerosol mass produced by the altered street cleaning frequency and methods used during the study period.

5.3.5 Summary of Street Sweeping Assessment Results

Traffic-related sources have been shown to account for approximately 40% of the TSP levels measured at the study sites. Baseline period and Control site measurements were included in the study so as to allow for the contribution of other sources in this assessment of street sweeping effects on TSP levels.

The higher loadings occurring during the mechanical sweeping period can be attributed to factors other than the increased frequency of sweeping on the basis of observations at the Control site, statistical evaluation of the data, CMB results, and dispersion modelling.

However, the small elevation in mean percent road dust (coarse) contribution at the Experimental site relative to the Control site during mechanical sweeping is statistically significant. Likewise, the small decrease in mean percent road dust contribution at the Experimental site relative to the Control site during vacuum sweeping is also statistically significant.

Geometric mean TSP values for the vacuum sweeping period show a decrease of approximately 7% at the Experimental site, and statistical evaluation of the data indicates that this decrease can be considered marginally significant at the 95% confidence interval. The disperion modelling results also can be interpreted to support this conclusion. However, statistical evaluation of the data for a specific set of conditions which could be expected to emphasize the impact of reentrained road dust on TSP levels showed no significant difference between the Experimental and Control sites. The dispersion modelling results indicate that a substantial reduction (∿ 30%) in the road dust contribution would have to be realized to result in the 7% reduction observed during the vacuum sweeping period. Although increased frequency of vacuum sweeping may have resulted in a small decrease in TSP levels, more frequent sweeping of roads and streets is unlikely to be an effective approach to the control of airborne particulate matter in most urban areas, unless undertaken as part of a comprehensive program which addresses all source categories.

The higher ambient concentrations during the [illegible] can be attributed to factors other than the increased frequency of [illegible] on the basis of comparisons with the control site, statistical evaluation of the data for [illegible], and dispersion modelling.

However, the small variation in mean concentrations [illegible] at the [illegible] sites relative to the control site, having [illegible]. Conversely, the small decrease [illegible] levels.

[illegible]

[illegible] were produced by the [illegible] the study period.

[illegible] Summary [illegible]

[illegible] of the TSP levels measured at the [illegible] site measurements were included in the study so as to allow [illegible] contribution of other portions of this assessment [illegible] on TSP levels.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Sources and Characteristics of Particulate Matter in Hamilton

Two of the specific objectives of the study have been to characterize, in some detail, airborne particulate matter in the Hamilton area and to make a quantitative assessment of the importance of non-traditional sources, with special emphasis on reentrained road dust. These objectives have been addressed in Sections 5.1 and 5.2, respectively.

The principal features of airborne particulate matter in Hamilton during the study period can be summarized as follows:

- the TSP levels measured at each site were found to follow log-normal distributions, indicating large scale or general influences rather than a specific predominant source.
- TSP levels at the study sites were consistent with historical MOE data for the downtown Hamilton area.
- Temporal plots or TSP concentrations for the Experimental and Control sites indicated that the two sites were relatively similar.
- Highest TSP levels at the Cannon St. sites occurred when winds were from the northeast at low to moderate speeds during periods of no rainfall. These conditions are conducive to transport of pollutants from the heavy industry sector to the receptor sites. TSP levels at the Farm site were also elevated under these conditions reflecting the effect of transport of pollutants from the downtown Hamilton area under these particular meteorological conditions. TSP levels for the School site were highest when winds were from the southwest indicating transport of pollutants from the industrial sector to this site under these conditions. These general conclusions are supported by several assessments of the data relative to prevailing meteorological conditions and other features.
- Consistent daily variations occur in the TSP data at all sites, with the highest levels observed during the afternoon. These variations are attributed to diurnal variations in wind speed and source

emission rates and, to a lesser extent, increased traffic activity during the daytime.

- **TSP levels show an anticipated decrease with height above the roadway and with distance away from the roadway.**
- **Average levels of both fine and coarse particulate loadings as measured by the dichotomous sampler occurred under northeasterly wind conditions. However, the fine to coarse particle mass ratio is lowest under northwesterly wind conditions, consistent with a reduced importance of secondary aerosols carried by long-range transport into the area under these conditions. In contrast, low F/C ratios are observed for high wind and no precipitation conditions, presumably the result of elevated coarse particulate levels.**
- **Overall, the size specific particulate matter data show that the 15 μm aerodynamic diameter and smaller fraction comprises approximately 45% of the TSP, with the "fine" fraction (< 2.5 μm aerodynamic diameter) comprising approximately 22% of TSP.**
- **Nitrate and sulphate data are similar at all sites across the Hamilton airshed. This indicates that long-range transport of secondary aerosol is the major contributor of these components.**
- **The results of the tracer experiment with europium chloride showed that europium concentration levels decreased with distance from the roadway, confirming the local effect of reentrained road dust.**
- **Morphological analysis of a selected subset of filters confirms the effect of wind direction on observed particulate matter levels and composition.**
- **Carbon comprises 5 to 25% of TSP levels in the Hamilton area.**
- **Approximately 5% of the dust on the road surface of Cannon St. was found to be in the reentrainable (< 37 μm) size range (215,243).**

A quantative assessment of the importance of non-traditional sources relative to industrial point source emissions was an important objective of the

study. Evaluation of the general features of the aerometric data, preparation of a microinventory, chemical mass balance determinations and dispersion modelling were the princiapl techniques used to quantify the contribution of various source categories to TSP levels in the study area. The major conclusions of these studies are as follows:

- Microinventory, chemical mass balance and dispersion modelling source apportionment results shows reasonally good agreement among the three methods.
- The largest contribution of particulate matter to the modelled receptors over the study period was from traffic related sources with an average contribution of about 40% of observed particulate levels. Reentrainment accounted for about 25% and vehicular exhaust about 15%.
- Background sources of particles account for ∿ 35% of observed levels based upon TSP measurements at the background sites, microinventory estimates and dispersion modelling. CMB predicts 30% in terms of ammonium sulphate, but 25% of the particulate matter is unexplained by the CMB method, and it is estimated that background aerosol components could represent another 12%.
- Area sources average about 10% of the aerosol mass, with point sources contributing somewhat less than 10%.
- Long-range transported sulphate is a major contributor to the fine particulate aerosol.

6.2 Particulate Matter Abatement Strategies

Historically, relatively little attention has been focused on control on non-traditional sources of particular matter. Awareness of the nature and extent of these sources has been limited and potential control measures generally have not been implemented. This study has demonstrated the extent of the particulate matter problem and characterized the major sources of particulate matter. The results point to the need for a compreshensive strategy designed to control a variety of sources of particulate matter in an urban area, including non-traditional sources.

The experimental and modelling results of the study indicate that, for the downtown Hamilton area, the average relative contribution of particulate matter source categories is as follows:

Source Category	Estimated % Contribution
Area	10
Point	∿ 7
Traffic-related	40
Background	35

These source categories contain several source types. Included in the area sources are the combustion sources of residential, commercial and industrial fuel combustion, incinerators, railroad diesel emissions, emissions from shipping, and the fugitive dust sources from railroad yards, unpaved roads and laneways, unpaved parking lots, unpaved storage areas, aggregate storage areas, elevated or exposed areas, construction and demolition sites and agricultural activities. Point sources refer primarily to emissions from stacks. Traffic-related sources include automobile and diesel truck exhaust emissions and reentrained street dust. Background includes any other sources outside the study area but still impacting on it, including long-range transported pollutants. Some control options that can be considered for each source category are discussed below.

Point: These sources are well identified and are already controlled to varying degrees. Further reductions in emissions from these sources are not likely to achieve significant improvements in ambient air quality in most urban areas, except to reduce the intensity of high pollutant episodes occurring in conjunction with periods of adverse dispersion conditions. Although beyond the scope of this study, industrial fugitive emissions should be considered as part of any overall control strategy. These emissions can include process fugitive emissions as well as emissions from material handling, unloading and loading, open storage piles, plant roads and parking lots and general plant areas. Attention to these emissions is important in achieving acceptable particulate air quality, especially in areas close to the industrial sector.

Background: Little can be expected to be achieved by urban abatement strategies to control the impact of background contributions from outside the area of concern.

However, general abatement efforts on point and area sources on a regional basis should effect a slight improvement in background contributions by controlling emissions from sources just outside the area of interest. Also, as a large portion of the background componenet is due to long-range transported pollutants, any controls promulgated to control acid rain by limiting sulphur oxide and nitrogen oxide emissions in North America should have a secondary effect of reducing background levels of particulate matter.

Area: Railraod diesel emissions and emissions from shipping are generally considered insignificant contributors to ambient particulate levels. However, residential, commercial and industrial fuel combustion and incinerators can have substantial contributions. Adequate particulate control of these sources can generally be effected by ensuring optimization of the combustion process (including good routine maintenace procedures for the equipment).

Several different measures can be used to control area fugitive dust sources. For unpaved roads, parking lots, storage areas and cleared or exposed areas, the most effective measures are paving, oiling or seal-coating to limit wind entrainment and vehicle trackout for aggregate storage areas. Contouring of aggregate piles and installation of wind fences have been found to be effective in controlling wind entrainment of dust. Agricultural activities are not an important sources of particulate matter in Hamilton. However, for application to other areas where such emissions may be important, the control measures discussed in Section 2.8 can be implemented.

Construction and demolition sites have been shown to be a significant source of particulate emissions, especially from dirt trackout onto roadways. The most common measure to control emissions due to site activities, particularly during demolition, is water. However, this requires appreciable quantities of water, and has negative effects due to increased trackout of mud onto adjacent roadways. The best approach to control trackout during the excavation period of construction has been found to be the immediate cleanup of all mud and dirt carried onto adjacent roadways(216).

Traffic-Related: As discussed in previous sections, contribution from this source is approximately 40% in downtown Hamilton and is made up of 25% due to reentrained street dust and 15% due to exhaust emissions. Exhaust emissions from automobiles are expected to decline with the general trend toward more fuel-efficient cars. However, diesel exhaust can be a significant source of emissions, and with the trend towards the use of diesel engines in automobiles, this source category may require further examination and control. Methods to control reentrained street dust include the control of street dust origins and street cleaning. Although increased frequency of vacuum sweeping may result in a small decrease in TSP levels (Section 5.3), more frequent sweeping of roads and streets is unlikely to be an effective approach to the control of airborne particulate matter in most urban areas unless undertaken as part of a comprehensive program which addresses all major source categories. Control of street dust origins can be based on use of the following methods:

- the immediate removal of mud and dirt tracked out onto adjacent streets from construction/demolition sites, and unpaved roads and lots
- more selective application of sand and salt during the winter with immediate clean-up of residue when roads are dry
- keeping roads in good repair
- installation of curbing where not now in place, and vegetation of roadside areas to reduce particulate transport due to wind or other effects
- modification of traffic patterns.

All of these measures except for the latter are, to some extent, related to the ongoing activities and future goals of municipal public works departments. Thus, effective application of these measures requires agreements between these departments and air quality control agencies. Suitable modification of traffic patterns may not be a realizable goal in urban areas.

Summary: It is apparent that a broad approach must be taken to control particulat emissions in order to reduce TSP levels. Significant emissions of suspended particulate matter have been identified to be from area and traffic-related source which have not traditionally been controlled. The most effective control measures which can be implemented appear to be paving or otherwise surface-sealing of unpaved roads, parking lots or areas, the cleanup of mud trackout from construction demolition sites, good maintenance of roadways, and the selective application of de-icing compounds in winter, followed by cleanup in spring. The implementation of these measures requires cooperation between air quality agencies, municipal public works departments and the private sector.

6.3 Methodology for Evaluating Sources of Urban Particulate Matter

Most of the studies of urban particulate matter conducted over the past few years have been narrow in scope and in most cases have over-looked important aspects of the overall problem. One of the objectives of this study was to define appropriate methodologies for future studies which might be required in the on-going development and evaluation of particulate matter control strategies. Accordingly, both the experimental and data analysis phases of the study were quite broad in scope to allow for the evaluation of different approaches which can be used in urban particulate matter studies.

The major components of the Hamilton study can be categorized as follows:

- Total Suspended Particulate Sampling
- Particle Size Measurements
- Measurement of Meteorological Parameters
- Other Parameters
- Chemical and Physical Analysis of Particulate Matter Samples
- Tracer Studies
- Data Analysis - General Features
- Microinventory of Sources
- Dispersion Modelling
- Receptor Modelling
- Street sweeping Assessment

The comments to be made on each of these components which could be used in future studies must, of course, be considered in the context of the specific objectives of any particular study, and any special characteristics of the study area which might have an important influence on TSP levels.

Before discussing each of the above components, the relative merits of long-term versus short-term studies will be discussed. While the comprehensiv nature of the Hamilton study necessitated a relatively short-term study period, a more specific investigation would allow more flexibility with respect to study duration. Some of the more apparent advantages of a longer-term study are:

- seasonal patterns can be experimentally assessed.
- unavoidable disruptions in field work (late instrument deliveries, instrument failures, staffing problems, etc.) are less critical.
- more time available to optimize procedures.
- preliminary analysis of data with appropriate revisions to the program is a feasible approach.

In the final analysis, the specific objectives of a given study will determine to a great extent the relative mertis of short and long-term studies. Staffing considerations and budgetary restrictions are other factors that would have to be considered, although it should not be assumed that the longer-term study will necessarily be more expensive.

Total Suspended Particulate Sampling. As well as being the reference method for total suspended particulate measurements, high-volume sampling continues to be the only readily available and reliable method for such measurements. Difficulties continue to be reported in the use of more recently developed automated continuous monitors. The comprehensive high-volume sampling program which was a key compone of the Hamilton study proved to be an important and useful part of the study and it is recommended that this method continue to be used in such studies.

Specific aspects of high-volume sampling to consider are:

- It is strongly recommended that a sampling period of 6-hours, rather than the usual 24-hours be used for such special studies. Improved time resolution, definition of diurnal patterns, and improved correlation with the other parameters (meteorological, etc.) are some of the advantages of shorter term sampling.

- anticipated diurnal patterns should be taken into account when selecting the sampling period and cycle.
- consideration of the relative importance of the various components of local "area" and "line" sources in sampler location. For most studies vertical and horizontal profiling probably can be given less emphasis than in the Hamilton study.
- the relative merits of fewer sampling sites in favour of a longer sampling period also should be considered.

Particle Size Measurements. The determination of particle size distributions is an essential component of any study concerned with the characterization of atmospheric particulate matter. The dichotomous sampler, based upon a single stage virtual impactor, eliminates most of the difficulties associated with earlier techniques, and the two size fractions (15μ to 2.5μ and < 2.5μ) in conjunction with conventional HiVol measurements, provide sufficiently detailed size distribution information for most studies. The compatibility of this technique with the CMB receptor modelling method should also be noted.

When the use of automated versions of the dichotomous samplers is planned, adequate time must be allowed for instrument start-up, the elimination of operational problems, and the establishment of filter handling and weighing procedures. The recently developed HiVol Size Selective Inlet (15μ cut-off diameter) is a less expensive alternative to the dichotomous sampler. Simplicity and ease of use are the obvious advantages of this method, but no information on the finer fraction of particles (i.e., < 2.5μ), is provided. Also, a comprehensive elemental analysis required for CMB work on the collected sample would be difficult to obtain in a cost-effective manner since the filter substrate normally used would not be fully compatible with XRF methods.

Meteorological Measurements. The documentation of prevailing meteorological conditions is an essential component of virtually any ambient air quality study and the question to be addressed is one of scope and content. In most urban areas, it usually is possible to obtain meteorological data representative of the general area from ongoing monitoring programs (Environment Canada, provincial control agencies, airports, etc.). Wind direction, wind speed (both upper and ground level), atmospheric stability and precipitation are the parameters most directly relevant to urban particulate characterization studies, and in most instances it will be desirable to measure these parameters at one site in the immediate vicinity of the study area.

Special attention must be given to the siting of low level (10 m) wind instrumentation in an urban setting (influence of tall buildings, etc.) and the resulting data must be interpreted and used with a constant awareness of these potential influences. As in the Hamilton study, it usually will prove desirable to use upper level wind measurements to define generally prevailing wind condition in the study area.

Synoptic weather forecasts and summaries, air mass trajectories and mixing heights are some of the other meteorological resources that could prove useful in particulate studies. However, the utility of such information would depend primarily upon the scale and specific objectives (quantitative definition of long-range transport contribution, region scale modelling, etc.) of the study.

Other Measurements. A number of ancillary pollutant and other parameters were measured during the Hamilton study with the intention of using these measurements to better assess the relative importance of various source categories and understand the dispersion processes involved. These included:

- traffic volume on major streets in the study area
- carbon monoxide levels
- coefficient of haze
- dustfall.

The traffic volume measuremnts proved very relevant to both the micro-inventory and dispersion modelling components of the study and should be included in any study concerned with the documentation of line source contributions to the atmospheric particulate burden. The other parameters did not prove particularly useful and it is recommended that they not be included in future studies. Carbon monoxide monitoring may, in other instances, prove useful as a tracer of automotive contributions.

Chemical & Physical Analysis of Particulate Samples. The complex, and variable composition of airborne particles is one of the more difficult aspects of the urba particulate matter problem. During the past decade, major advances have been made in the application of several chemical and physical techniques to the characterization of airborne particles, resulting in a better understanding of such factors as:

- composition versus particle size
- the dependence of composition on source type
- the predominant role that materials of non-anthropogenic origin can play in particulate matter composition.

Optical microscopy, X-ray fluorescence (XRF), atomic absorption spectroscopy (AA), neutron activation analysis (NAA), ion chromatography (IC) and carbon analysis all have been used in the Hamilton study and in each case have provided information useful to the objectives of the study. Selectivity is the key to cost-effective use of these analytical methods and this can be achieved in the following ways:

- by being aware of filter media limitations relative to analysis for specific chemical constituents.
- by using those methods best suited to the specific objectives of the study. Optical microscopy, for example, is an ideal qualitative approach for the identification of predominant constituents (and hence predominant source categories), whereas multi-element analysis by a method such as XRF is necessary for the more quantitative CMB approach to source apportionment. Ion chromatography, on the other hand, is ideally suited for the quantitative determination of ionic constituents such as sulphate and nitrate which account for a major proportion of the background contributions.
- by conducting preliminary analysis of a relatively small subset of filters and rejecting those parameters unlikely to yield useful information. High or variable filter blank levels and low or essentially constant sample levels are three conditions which limit the usefulness of chemical analyses.

- by selecting subsets of filters for analysis on the basis of meteorological regimes (as in the Hamilton study) or other relevant selection criteria.

Tracer Studies. The release of inert tracer constituents has long been recognized as a useful technique to define atmospheric dispersion parameters and differentiat physical dispersion from other atmospheric processes (deposition, reaction, etc.). The feasibility of using tracer techniques to assess the reentrainment of particle from roadways has been assessed briefly in the Hamilton study. The method shows considerable promise in terms of defining the contribution of a specific component of a general source category (for example, the contribution being made by one of several roadways, or other source types, in a study area). However, the method needs further definition and a better understanding of the reentrainment mechanism before it can be used to quantitatively define emission rates and apportion source contributions. Some of the questions that must be answered are:

- is the tracer/TSP reentrainment ratio independent of TSP loading?
- what are the different tracer and road dust loading profiles across the street surface?
- how best to allow for changing weather conditions during the period of interest following the known tracer application?

Data Analysis - General Features. Interpretation and analysis of the general features of the data provides an overview of prevailing particulate matter levels and the manner in which they depend on meteorological and other factors. Useful approaches include the calculation of average levels to permit comparisons between sites and with historical data for the area, diurnal and other temporal patterns, evaluation of specific esisodes, directional distributions, and assignment of monitoring periods to meteorological regimes. A specific time allocation should be made to such assessments of the data collected in any urban particulate study.

Microinventory. The purpose of a microinventory is to consolidate information on sources, land use characteristics and monitoring siting which can then be used to identify and define the relative importance of the various sources in the study area. In the Hamilton study, use of the microinventory technique resulted in a quantitative documentation of sources in the study area which was of considerable use in subsequent sections of the study, especially in the preparation of a source matrix for the dispersion model. The estimated contributions of the various source categories also were in good agreement with the results of other modelling techniques.

The microinventory technique is a useful component of any particulate study concerned with the definition of the relative importance of non-traditional sources. However, the essentially empirical and statistical nature of the method must be kept in mind in determining the emphasis to be given to this approach. Quantitative prediction of TSP levels cannot be expected without a very extensive and long-term monitoring program. It should be noted that the existence of an extensive ongoing TSP survey does offer the possibility of applying this method with a modest effort and cost. Thus, the specific objectives and circumstances of a study must be considered to determine the appropriate use of the microinventory approach.

Dispersion Modelling. As discussed above, the empirical microinventory technique could not provide the discriminatory capability required to analyze the complex interactions of various source categories and meteorological conditions present in the Hamilton study. The PAL model is a comprehensive analytical model for the local scale, including point area and line source components, and provided a time and spatial resolution compatible with the objectives of the Hamilton study. The model helped to explain observed variations in TSP loadings as a function of emission and meteorological factors, and the predicted relative contributions of the various source categories were in good agreement with the results obtained by other methods. The model tended to overpredict TSP levels and some difficulty was explained in assigning an appropriate height factor for area sources and a background contribution factor.

The cost-effective application of dispersion modelling to particulate characterization studies is feasible provided that:

- a general purpose model of the appropriate scale and time resolution is available in a form requiring a realistic level of effort for adaptation to the specific conditions of the study.
- the source emission inventory and other pertinent input data are

prepared in a format compatible with the model at the outset of the study.

A dispersion model such as PAL can be used to:

- explain the temporal and spatial dependence of TSP loadings as a function of source emission rates and meteorological conditions.
- estimate the relative importance of point, area and line source contributions at specified receptor sites.
- predict, on a relative basis, the effectiveness of various control strategies that might be proposed.

Receptor Modelling. Receptor modelling is a recently developed technique which complements dispersion modelling and can also be used to assess the impact of source types on air quality. The chemical mass balance (CMB) method is a versatile receptor model that makes direct use of detailed chemical composition to relate ambient particle loadings to specific sources or source types. In the Hamilton study, the CMB method proved to be an efficient method to identify the predominant source categories of airborne particulate matter, and the resulting source apportionment was in good agreement with the dispersion model and micro-inventory predictions despite the general lack of specific information on the chemical composition of emissions in the Hamilton area.

The CMB approach to source apportionment is recommended as an efficient and versatile technique which should be used in future urban particulate studies. In the design of the study attention should be given to the following specific needs of this approach:

- dichotomous particulate sampling
- source characterization, using selective chemical analysis of both traditional and non-traditional source emissions
- selective chemical analysis of an adequate dichotomous filter set.

Street Sweeping Assessment. A quantitative assessment of the effect of more frequent street sweeping on local TSP levels was one of the objectives of the Hamilton study. The study design included both a baseline monitoring period and measurements at a control site to allow for other factors which might cause variations in TSP levels during the study period. While increased frequency of mechanical sweeping showed no effect on TSP levels, it appears that vacuum sweeping may have resulted in a small decrease, but as discussed in previous sections, the difference is of only marginal significance.

Traffic related sources have been shown to account for approximately 40% of the TSP burden and it is apparent from the results that a substantial reduction (approximately 30%) in the reentrained road dust contribution would have to be achieved in order that a statistically significant change occur in ambient TSP levels. While some features of the data suggest that vacuum sweeping may indeed have achieved a reduction of this magnitude, it has not proven feasible to quantitatively document the effectiveness of more frequent street sweeping as a particulate control strategy. The presence of other sources of comparable importance and a normal degree of variability in the ambient TSP measurements are the principal factors which prevent a more conclusive assessment from being made. Similar circumstances are likely to prevail in other urban areas and so it is recommended that intensive short-term evaluation of alternate control strategies for non-traditional sources of TSP (streets, parking lots, etc.) not be included in future studies on a routine basis. Cases in which a specific source category clearly dominated would be an exception to this recommendation. Longer term evaluations might also be more appropriate for the evaluation of specific components of overall, alternate control strategies.

Summary. To summarize, most of the components of the comprehensive Hamilton study have proven relevant to the objectives and goals defined at the outset of the program. The experience gained can now be used to define more specific studies which might be required in the further development of particulate control strategies. In designing such studies, the relative merits of long and short-term studies must be assessed in terms of the specific requirements at hand. TSP monitoring, particle size measurement, basic meteorological measurements and selective chemical analysis of the collected samples are likely to be desirable components of most studies. A comprehensive evaluation of the general features of the data should be a well-defined component of the study, and the results can be used to determine more specific assessments to pursue. The preparation of a microinventory of sources, dispersion modelling, and receptor modelling are specific approaches which can be used to make source apportionments and the merits of each must be assessed relative to the data base available and the specific needs of the study.

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